MONTHLY WEATHER REVIEW

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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: $3.00; additional for foreign mailing, $1.00; 30¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

The printing of this publication has been approved by the Director of the Bureau of the Budget, February 9, 1955.

DEPARTMENT OF COMMERCE
SINCLAIR WEEKS, Secretary

WEATHER BUREAU
F. W. REICHELDERFER, Chief

MONTHLY WEATHER REVIEW

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THE ECONOMIC UTILITY OF WEATHER FORECASTS

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ABSTRACT

The economic factors involved in the use of weather forecasts are discussed, and procedures for analyzing the economic utility of both probability and categorical forecasts are derived. Some of the considerations involved in making public forecasting decisions are presented, and expressions are suggested for assessing the economic utility of public forecasts. The relationships between these measures of economic usefulness and certain formulae frequently used to assess forecasting accuracy are also pointed out.

1. INTRODUCTION

One of the problems which, from time to time, has faced the meteorologist is the need for measuring his ability to predict the state of the atmosphere in order that the value of his scientific effort may be demonstrated. This requirement has resulted in a number of studies aimed at devising "verification systems" whose principal purpose has been to assess the accuracy of the prediction. Since this requires that such accuracy be defined, often quite arbitrarily, it is not an uncommon experience to find that a group of forecasts which may show a high verification score need not necessarily be economically useful predictions [1].

It is therefore the purpose of this paper to present a method of analysis designed to measure the economic utility of the forecast, and to suggest a verification procedure based upon the operational risks involved in taking protective measures against adverse weather. In this way, the definition of forecasting accuracy may be made synonomous with economic usefulness, thus overcoming the difficulty.

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2. AN ECONOMIC DECISION CRITERION

Consider the general case of a potential user of a weather forecast faced with the problem of deciding whether or not to take protective measures against a certain adverse weather element, W. In general, he should take such protective measures if, in the long run, some economic gain will be realized; otherwise no protective measures should be taken. In order to derive a criterion for making this decision, the following terms are defined:

G_p =Total expected gain for $N=(f_w+f_{nw})$ days of operation if protective measures are taken every day,

G_{np}=Total expected gain for N days if no protective measures are taken,

C =Cost of protection each day that protective measures are taken,

L =Loss suffered each day that adverse weather occurs and no protective measures have been taken,

T =Average daily net operating income exclusive of the cost of protection (C) which may have been taken, or the loss (L) which may have been suffered,

f_w =Frequency of adverse weather,

f_{nw} =Frequency of favorable weather.

If, now, protective measures are taken every day, the total gain will be the daily net operating income minus the daily cost of protection, both times N, the number of days of operation. Thus,

$$G_p=(T-C)N. \tag{1}$$

If no protective measures are taken, it will be apparent that,

$$G_{np}=(T-L)f_w+Tf_{nw}. \tag{2}$$

The total gain to maximize the profit on the entire operation should be as large as possible; thus protective measures should be taken whenever $G_p>G_{np}$ or, from (1) and (2), protection would be required if

$$(T-C)N>(T-L)f_w+Tf_{nw}.$$

This reduces to

$$\frac{f_w}{N}>\frac{C}{L}.$$

The left-hand side of this inequality defines P, the "probability" of adverse weather [2]. In a similar manner it may be shown that protective measures should not be taken if $P<C/L$, and the total gain would be equal whether or not such measures were taken if $P=C/L$. Thus the criterion for making a decision to protect or not protect may be expressed

$$P\begin{Bmatrix} > \\ = \\ < \end{Bmatrix}\frac{C}{L}\begin{cases}\text{Protect}\\ \text{Either course}\\ \text{Not protect}\end{cases} \tag{3}$$

The value $P=C/L$ therefore represents a critical ratio, above which protection should be provided, and below which it should not. It is interesting to note that for C, L, and T, as defined here, the last drops out and need not be considered in making the decision. Alternative, but generally more complex, expressions may be derived by defining these terms in a different manner, e. g., Gringorton [3].

3. THE ECONOMICS OF WEATHER FORECASTS

The results of a series of N categorical forecasts are presented in a generalized form in table 1. Here W and No W are defined as the occurrence and non-occurrence, respectively, of an operationally critical weather event, and a, b, c, d, represent the frequencies in the indicated boxes in the table.

From table 1, the climatological probability, P_c, of observing a critical weather event is given by

$$P_c=\frac{c+d}{N}. \tag{4}$$

From equation (3) it is seen that, if $P_c>C/L$ and climatological expectancy is used as a basis for the decision,

TABLE 1.—*Generalized two-class forecast—observed contingency table.*

		FORECAST		
		No W	W	Total
OBSERVED	No W	a	b	$a+b$
	W	c	d	$c+d$
	Total	$a+c$	$b+d$	$N=a+b+c+d$

protection should be provided every day. In this case there is no loss, and the total expense for the operation E_p, for N days is given by

$$E_p=CN \tag{5}$$

When $P_c<C/L$, no protective measures should be taken, and a loss will be suffered every day that W occurs. The total expense for the operation in this case is

$$E_{p'}=L(c+d) \tag{6}$$

If, on the other hand, the decision is based on the forecasts in table 1, the total expense for the operation, E_f, will be due to the cost of protection whenever W is forecast plus the loss due to missed predictions. Thus

$$E_f=C(b+d)+Lc. \tag{7}$$

As a matter of interest, it should be noted that this expression could be used in assessing the economic utility of a weather forecast [4, 5]. It suffers, however, from two limitations: (a) It provides no inherent frame of reference by which the utility of the forecast is compared with another method of making a decision; and (b) since it measures the expense of the operation, the best forecast is obtained with the lowest value of E_f. If, however, it is noted that equations (5) and (6) give the operational expense for decisions based on climatology, and if the operational expense resulting from the use of the forecasts is compared with these expressions in the proper way, the economic saving over climatology can be obtained, thus providing a more useful measure of forecast utility.

When $P_c\geq C/L$, the economic saving over climatology, S_1, per unit forecast per unit of loss is given by

$$S_1=\frac{E_p-E_f}{NL}.$$

Using equations (5) and (7), the above expression may be simplified in the following form and used to measure the economic usefulness of the forecast:

$$S_1=\frac{a+c}{N}\left(\frac{C}{L}-\frac{c}{a+c}\right)\quad \text{(Use when } P_c\geq C/L\text{)}. \tag{8}$$

In a similar manner, when $P_c\leq C/L$, the economic saving over climatology, S_2, is

$$S_2=\frac{E_{p'}-E_f}{NL}$$

or,

$$(9)\quad S_2=\frac{a+c}{N}\left(\frac{C}{L}-\frac{c}{a+c}\right)+\left(P_c-\frac{C}{L}\right)\ \text{(Use when } P_c\leq C/L\text{)}.$$

Equations (8) and (9) now provide a quantitative measure of the value of any categorical weather prediction where the relative economic risks, C/L, are specified. If the loss, L, is expressed in dollars, the quantity S_1 or S_2 gives the number of dollars saved over climatology for each forecast issued.

4. ECONOMIC GAINS FOR PROBABILITY FORECASTS

If verification data are available for a series of probability forecasts, it is possible to compute the economic value of the forecasts for any given value of the economic risks, C/L, using equations (8) and (9). In this case, the forecasts may be placed in a contingency table similar to table 1, but with the decision to forecast W or No W being based upon the value of C/L (and therefore of P) selected:

TABLE 2.—*Generalized contingency table for use with probability forecasts*

		FORECAST PROBABILITY		
		$P\leq C/L$	$P>C/L$	Total
OBSERVED	No W	a	b	$a+b$
	W	c	d	$c+d$
	Total	$a+c$	$b+d$	$N=a+b+c+d$

Where it is desired to compute the economic saving for a number of values of C/L, it is convenient to make the computations by cumulating the forecast and observed critical weather frequencies, thus permitting carrying out the computations in a single table. Table 3 shows an example of such computations using a series of experimental forecasts of the probability of occurrence of minimum temperatures 32° F. or less for a selected station during the winter months of 1950–51. The climatological relative frequency, P_c, from the observed series was 0.64.

TABLE 3.—*Verification data and computation of economic savings for probability forecasts of minimum temperatures at a selected station for December 1950, January and February 1951. (Data for one day missing)*

Forecast probability	No. of forecasts	Accumulated forecasts	Accumulated occurrences of $T\leq32°$	$\frac{a+c}{N}$	$\frac{c}{a+c}$	(P_c-C/L)	S
0.05	11	11	1	0.1236	0.0909	....	−0.01
.15	9	20	1	.2247	.0500	....	.02
.25	6	26	2	.2921	.0769	....	.05
.35	1	27	2	.3034	.0741	....	.08
.45	5	32	6	.3596	.1875	....	.09
.55	10	42	15	.4719	.3571	....	.09
.65	6	48	18	.5393	.3750	−0.01	.14
.75	9	57	27	.6404	.4737	−.11	.07
.85	6	63	31	.7079	.4921	−.21	.04
.92	9	72	40	.8090	.5556	−.28	.01
.97	17	89	57	1.0000	.6404	−.33	.00

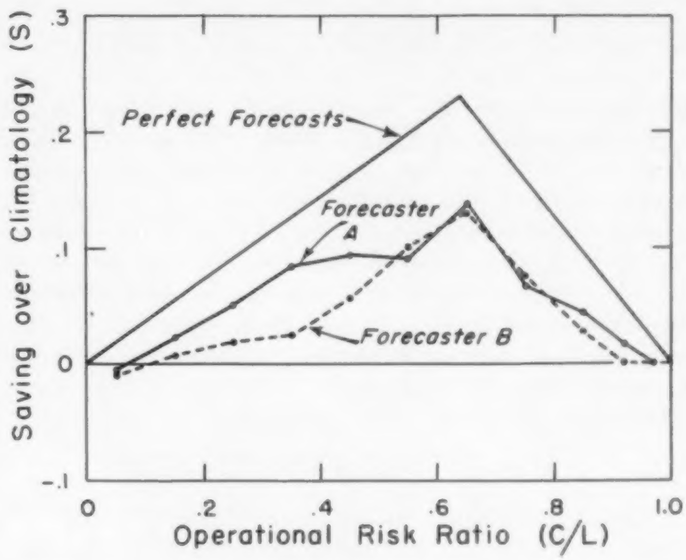

FIGURE 1.—Saving over climatology for a series of experimental probability predictions made by two different forecasters, A and B. Forecasts were made for temperatures 32° F. or lower at a selected station during the winter months of 1950–51.

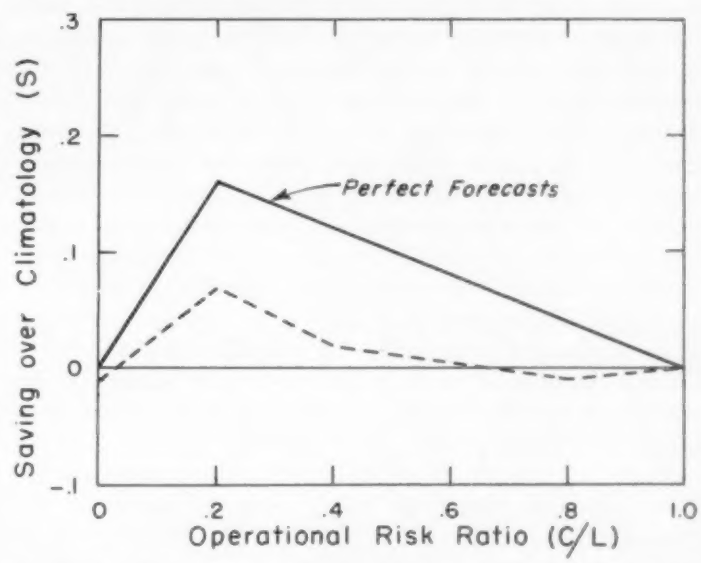

FIGURE 2.—Saving over climatology for a series of probability predictions discussed by Williams [6]. Forecasts were made for precipitation at Salt Lake City.

Figure 1 is a graph of these data (Forecaster A) and data for a similar set of probability forecasts made by another individual (Forecaster B). The maximum savings over climatology for perfect forecasts are also shown.

Figure 2 shows the savings for a group of precipitation forecasts discussed by Williams [6]. It will be noted that the utility of these forecasts would be limited to operations whose relative economic risks would range between 0.05 and 0.6, approximately.

It is also of interest to note that the maximum economic saving occurs where the ratio C/L is numerically equal to the climatological probability of adverse weather. An inspection of equations (8) and (9) will show that S_1 has a positive, and S_2 a negative, linear relationship to C/L. Since the useful portion of S_1 is limited to the segment between $C/L=0$ and its intersection with S_2 at $C/L=P_c$, while the useful part of S_2 ranges between the latter value and $C/L=1$, the maximum economic gain for any given set of forecasts will occur where the relative economic risks are equal to the climatological expectancy. This suggests that weather forecasts in general will have the greatest chance of being useful, as defined in this paper, when made for operations of this kind.

5. PUBLIC FORECASTING DECISIONS

Although, as shown by Ogarawa [7], the economic advantages inherent in the use of probability forecasts are undeniable, there are several practical difficulties which appear to inhibit the issuance of probability estimates for general public use—at least for the present. Among these difficulties are the lack of experience on the part of the forecasters in issuing probability forecasts, the need for public education regarding their use, and a number of technical difficulties arising from the necessity for simplifying a somewhat complex concept without invalidating certain basic principles. Furthermore, it seems likely that even if a simple probability forecasting system were devised for general use, a large percentage of the public, following an economically unsound but mentally less fatiguing policy of letting the forecaster make their operating decisions for them, would ignore the probability aspects of the forecast and continue to use the prediction as a categorical statement. It would, therefore, be of interest to present some of the general principles which relate categorical forecasts to the overall economic considerations which govern their optimum use.

From the previous discussion, it is evident that a categorical forecast should be based upon the nature of the economic risks, C/L, applicable to the operation for which the forecast is being issued. This ratio for a single forecast user may be obtained from an analysis of the operation. It is interesting to speculate, however, concerning the optimum value of C/L for a series of public forecasts where a wide range of operations is involved. Two such values are worth mentioning here.

In order to make economic sense, the ratio C/L can be shown to have a total range between zero and unity. Consider, for example, the possibility that $C/L>1$. In this case, the cost of protection, C, would exceed the loss, L, and it would obviously be uneconomic to consider protecting against adverse weather at all. In a similar way, it will be seen that negative values of C/L are economically meaningless.

Since $0\leq C/L\leq 1$, if it were assumed that the relative risks involved in making decisions for the usual day-to-day public forecasts would include this entire range, and that all values of the ratio C/L were equally important, then it might be suggested that the categorical prediction of greatest overall public usefulness would be obtained if the decision to forecast critical weather were made when this ratio is near the middle of the range, i. e., when $C/L=.50$. Inserting this value in equations (8) and (9) gives the very simple expressions:

$$S_{1(C/L=.5)}=\frac{a-c}{2N} \qquad \text{(Use when } P_c\geq .5) \tag{10}$$

$$S_{2(C/L=.5)}=\frac{d-b}{2N} \qquad \text{(Use when } P_c\leq .5) \tag{11}$$

Thus, if the forecaster bases his decision to forecast rain or no-rain, say, on the basis that the chances are greater or less than even, i. e., that the probability of rain is greater or less than .50, equation (3) states that such forecasts have been designed for operations where the value of C/L is likewise near .50. Equations (10) or (11) then provide a quantitative measure of the economic value of the predictions. As a rule (but not necessarily), selecting the decision criterion at the .50 probability level will result in the prediction of adverse and favorable weather with about the same frequencies as they occur, i. e., in table 1 $(b+d)$ will be approximately equal to $(c+d)$. This is equivalent, in the usual forecast terminology, to saying that adverse weather will be neither "under-forecast" nor "over-forecast," a procedure which is considered by many forecasters to be desirable, e. g., Schmidt [8].

Another interesting result is obtained if the ratio C/L is assumed to be near the climatological probability of adverse weather where, as pointed out earlier, the maximum economic gain will be realized. Accordingly, if P_c as defined in equation (4) is substituted for C/L in equations (8) or (9), the economic saving over climatology will be given by

$$S_{(C/L=P_c)}=\frac{ad-bc}{N^2}. \tag{12}$$

That it may be desirable to use the climatological expectancy as a basis for the decision to predict unfavorable weather is suggested by the fact that both agriculture and industry as well as the living habits of the people, tend to become adjusted to the normal climatic expectancy of various weather elements. In the San Joaquin Valley of California, for example, a thirty-five million dollar raisin crop is spread under the open sky for a period of four to six weeks on the strong climatic expectancy that no rain of consequence will occur during the early fall months. If rain does occur unexpectedly, however, the loss is so great, and the cost of covering or otherwise protecting the exposed crop so small, that the operational risk, C/L, is reduced to a very low value. This, in turn, means that the decision to issue rain warnings to the

growers should be made at a rather low probability level—perhaps near the climatological expectancy.

Similar examples for the public as a whole might be suggested, especially in the cases of destructively severe weather—hurricanes, tornadoes, blizzards, and the like—where the climatic frequency is also rather low. In these cases the general result of making the forecasting decision at the climatological probability level will be to "over-forecast" severe weather, i. e., in table 1 $(b+d)$ will usually be considerably greater than $(c+d)$.

It should be pointed out that every group of categorical forecasts is associated, explicitly or implicitly, with some value, or values, of the ratio C/L. For the most part, these factors are only vaguely incorporated in public forecasts at present. The values of C/L given here are suggested as interesting and perhaps, for some purposes, fairly realistic values.

6. ECONOMIC GAINS FOR PUBLIC FORECASTS

In order to give some idea of the order of magnitude of the economic gains which may result from the use of categorically issued public forecasts, the set of temperature forecasts in table 4 is reproduced from a previous paper [1]. These are the official forecasts for the same period as the experimental probability forecasts of table 3 and figure 1.

For $C/L=.50$ (since $P_c=\frac{57}{90}=.63>.50$, equation (10) is used):

$$S_{1(C/L=.5)}=\frac{27-6}{180}=.117$$

For $C/L=P_c$, using equation (12):

$$S_{(C/L=}P_{c)}=\frac{27\times51-6\times6}{90^2}=.166.$$

These values indicate that, for this set of predictions, savings of 11.7 and 16.6 cents per forecast, for each potential dollar of loss, would be obtained where the operational risks were near .50 and .63, respectively. As was shown in the previous paper [1] where these data were used, these forecasts would only be useful where $.18<C/L<.90$, approximately. For economic risks outside this range, values of S_1 and S_2 will be found to be negative.

TABLE 4.—*Minimum temperature forecast verifications at a selected station for the months of December, 1950; January and February, 1951*

		FORECAST		
		>32	≤32	Total
OBSERVED	>32	27	6	33
	≤32	6	51	57
	Total	33	57	90

7. RELATION TO OTHER MEASURES OF FORECASTING SKILL

As a matter of interest, it may be worth noting that equations (10), (11), and (12) are related to the percentage of correct forecasts A as follows:

$$S_{1(C/L=.5)}=\frac{1}{2}(A-P_c)$$

$$S_{2(C/L=.5)}=\frac{1}{2}[A-(1-P_c)]$$

$$S_{(C/L=P_c)}=\frac{1}{2}\left(A-\frac{E_c}{N}\right)$$

where $A=\frac{a+d}{N}$ and $E_c=\frac{(a+b)(a+c)+(c+d)(b+d)}{N}=$ number of forecasts expected correct by chance as determined by the marginal totals of table 1.

Equations (10), (11), and (12) are related to the conventional skill score S_c in the following manner:

$$S_{1(C/L=.5)}=\frac{1}{2}\left[\frac{E_c}{N}(1-S_c)+(S_c-P_c)\right]$$

$$S_{2(C/L=.5)}=\frac{1}{2}\left[\frac{E_c}{N}(1-S_c)+S_c-(1-P_c)\right]$$

$$S_{(C/L=P_c)}=\frac{1}{2}\left[S_c\left(1-\frac{E_c}{N}\right)\right]$$

where $S_c=\frac{(a+d)-E_c}{N-E_c}$.

Certain other alternative relationships between these variables may be shown with a little algebraic manipulation.

ACKNOWLEDGMENT

The authors wish to express their appreciation for suggestions received during discussions with Mr. R. A. Allen and Mr. E. M. Vernon.

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THE NORTH PLATTE VALLEY TORNADO OUTBREAK OF JUNE 27, 1955

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[Manuscript received October 24, 1955]

ABSTRACT

The largest and most devastating tornado in the history of western Nebraska occurred on June 27, 1955, in the North Platte Valley. The storm path and damage are described and two personal accounts of encounters with the center are presented. Selected pictures from a large collection of photographs are reproduced and used to determine the width and height of the funnel and of other features. Radar pictures show the characteristic "hook" or "number 6" appearance of the associated cloud. Aerial photographs of unusual markings apparently made by the tornado on a field near Scottsbluff are scaled and used with certain assumptions to obtain an estimated surface wind of 484 m. p. h. in the funnel. Information is given on observed downdrafts, sense of wind rotation, shape of the cloud protuberance, and associated weather conditions.

1. INTRODUCTION

Tornadoes are not strangers to western Nebraska but records indicate that tornadoes in that part of the State are usually small. They act more like large whirlwinds than real tornadoes. The natives call these "twisters." Rare indeed is the tornado that does more than scatter a hay stack or blow over an isolated farm building. The tornado situation of June 27, 1955, was a rare phenomenon for it produced the largest and most devastating tornado in the history of western Nebraska. In size and force this phenomenon was comparable to tornadoes in any State in the Union. Destruction was spread along the path from Henry, Nebr., near the Wyoming-Nebraska line, where a tornado struck at 3:30 p. m., MST, down the North Platte Valley to about 8 miles east of Scottsbluff, Nebr., where the largest of the observed funnels dissipated about 5:20 p. m., MST. This path is over 30 miles in length (see fig. 1).

2. PATH AND DAMAGE

The first sign of a tornado in Nebraska [1] on June 27 was observed by a local citizen at Henry, Nebr. He was looking west toward Wyoming watching a dark cloud moving toward him. As the cloud moved near it passed over a flooded field along the North Platte River, and a column of water spray was seen to rise up from the surface and form a column about 8 feet in height and 4 feet in diameter. The observer compared the water column to a shock of corn and reported that water appeared to spray upward and outward from the top of the column. Perhaps he was the first person ever to see a waterspout in Nebraska. He observed no funnel or proturberance below the cloud but time did not permit a complete study as the "waterspout" was moving directly toward the observer who, having been alerted to the possibility of a tornado, sought shelter. The occurrence of the "waterspout", its size, shape, and location, was verified by another observer.

A tornado moved directly over the village of Henry with damage only to cottonwood trees. These tall trees extended above the low buildings. It appeared as though a giant hand had reached down grasping the tree tops and pulled upward until the roots were freed from the soil and then the trees were dropped. Wood frame buildings under the trees were not damaged.

Over open fields to the east of Henry there was no sign of ground damage for 3 miles. To the south-southeast, where the terrain drops rather sharply from rolling country into the level valley, a tornado moved over a hill about 50 feet in height into the valley, passing directly over a small farm house. The roof was removed from the house and carried away. Two occupants reported that the house seemed "to shake, rumble, and roar" and though it was twisted from its foundation it remained upright. All other farm buildings, including a barn and two sheds, were completely destroyed and carried away. The house was nearer the hill than were the other buildings. In several instances along the tornado path there seemed to be a skip in the destruction on the downward side of a hill that the tornado had passed over.

The storm cell moved south-southeast for approximately 6 miles and then curved and moved directly east for 7 miles. Along this distance there was some wind damage but no evidence of a tornado funnel touching the ground. Seven funnels were observed at one time extending downward but not touching the ground in this section.

[1] A tornado was reported 14 miles northwest of Chugwater, Wyo., at 1 p. m., MST (*Climatological Data, National Summary*, vol. 6, No. 6, June 1955).

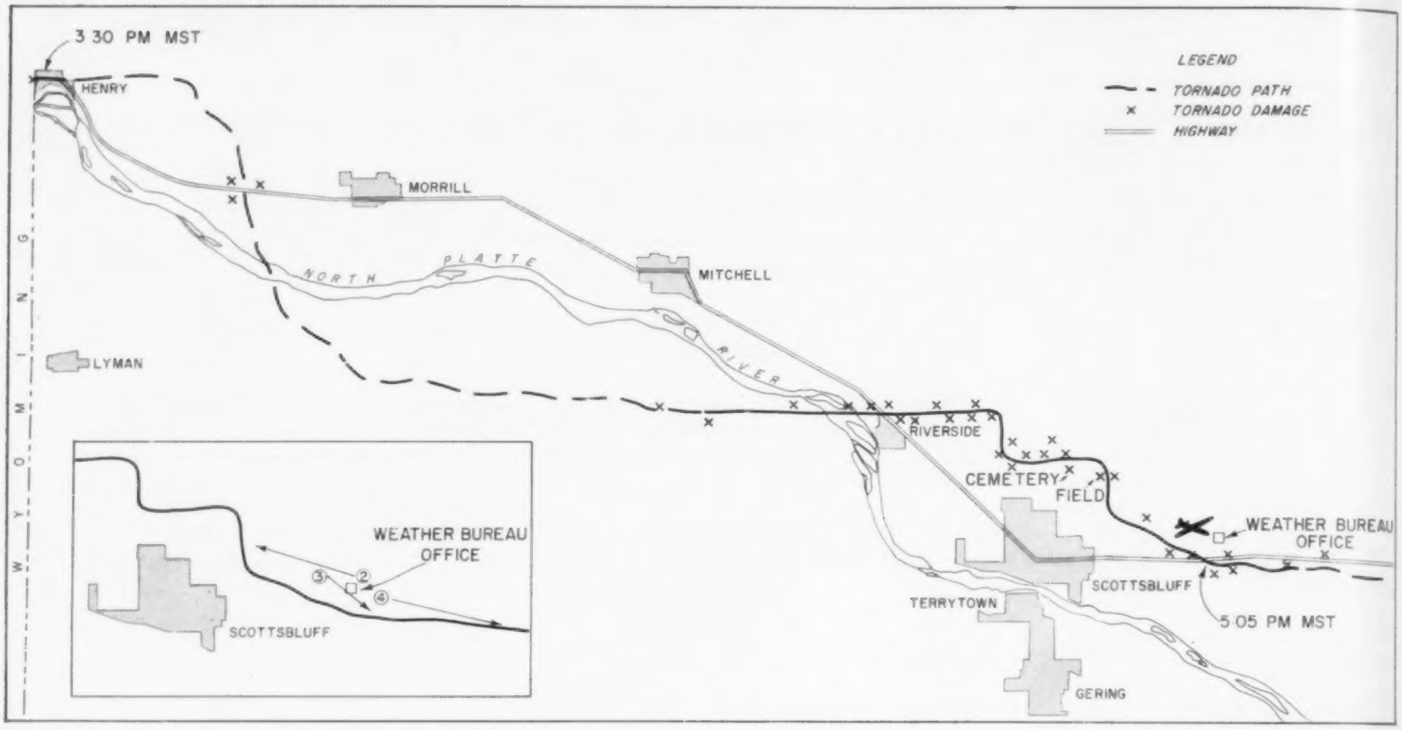

FIGURE 1.—Path of tornado destruction across Scotts Bluff County, June 27, 1955. The dashed portion of the path indicates no evidence of contact with the ground except at Henry and west of Morrill. This portion of the path was determined from photographs and from residents of the area who saw as many as seven funnels at one time along this route. The solid portion of the line indicates continuous contact with the ground. It is believed that north of Scottsbluff there was only one funnel in contact with the ground though there were one to three additional funnels in the same general vicinity that did not reach the ground. Inset shows position of photographer when pictures shown in figures 2, 3, and 4 were taken. Map scale: ¼ inch=1 mile.

From 2 miles south of Mitchell, Nebr., a funnel maintained contact with the ground until cloud dissipation 8 miles east of Scottsbluff. From south of Mitchell the tornado moved due east for 7 miles then turned at right angles to the south for 1 mile, then east for 2 miles, then south 1 mile, then southeast 2 miles, and then east until it faded away. The destructive width of the tornado varied from 200 to 400 yards with the greatest width damage north of Scottsbluff. As the tornado moved across the rural area of the North Platte Valley the only concentration of housing in its path was 3 miles east of Scottsbluff where a housing project of seventeen units, constructed along an irrigation ditch and right in line with the tornado path at this particular distance, was completely destroyed. Two lives were lost. A boy was killed by a truck being hurled upon him as he took refuge in a ditch, and a lady was killed when the car in which she was riding was caught in the tornado funnel. Forty persons were injured and 146 buildings were destroyed or damaged.

3. ENCOUNTERS WITH TORNADO CENTER

One of the injured may have had the experience of being in the center of a tornado funnel. The following is an account of his experience. He reports that while driving west on the highway east of Scottsbluff, he noticed a large dust cloud but he did not recognize anything ominous, having observed many more awesome dust clouds in the past; so he proceeded to drive into the dust cloud at a point 3 miles east of Scottsbluff. On entering the dust cloud he realized this was no ordinary disturbance and stopped the car at the side of the road. There was a roar and a crash of glass as the windshield and windows were broken by flying debris. He pulled his wife's head over in his lap and bent over to shield their faces. There was a moment of comparative calm and he raised his head to peer through the broken windshield. Large boards, tree limbs, and a boulder the size of a man's head were floating around the car. When asked the direction of movement he stated without hesitation that the debris was circulating to the left or counterclockwise. Time here was indefinite until there was a crash and that is all he remembers until he regained consciousness in a hospital. Actually both occupants were thrown from the car onto the highway. Both were badly cut and torn. The wife was apparently killed instantly. The car was rolled into an unshapen mass of metal and deposited in a nearby field.

Another case of contact or near contact with the center of the funnel was the experience of three men who were observing and reporting the funnel north of Scottsbluff from a commercial radio mobile broadcasting unit. These broadcasters were ahead of the funnel and to maintain

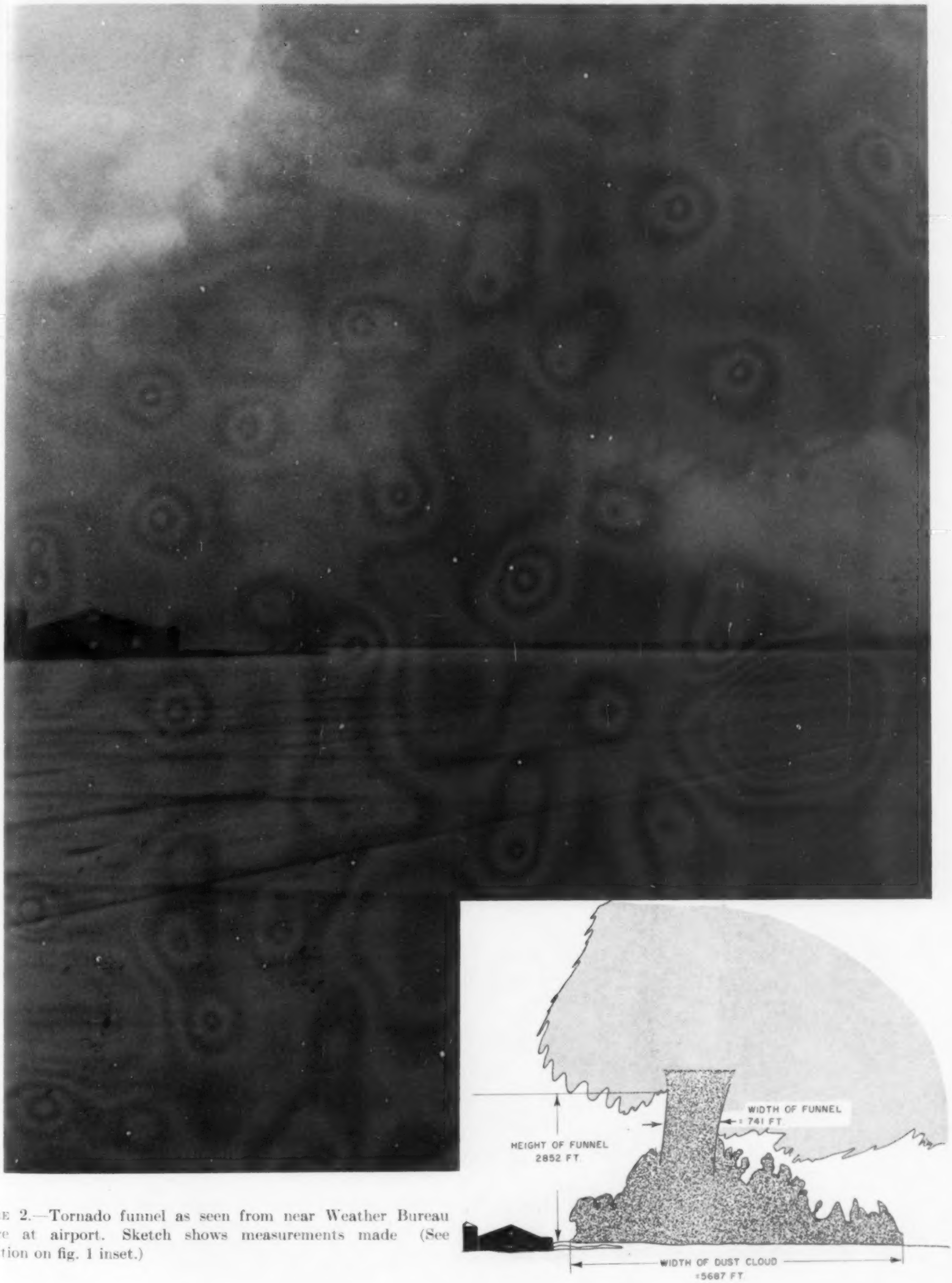

FIGURE 2.—Tornado funnel as seen from near Weather Bureau office at airport. Sketch shows measurements made (See position on fig. 1 inset.)

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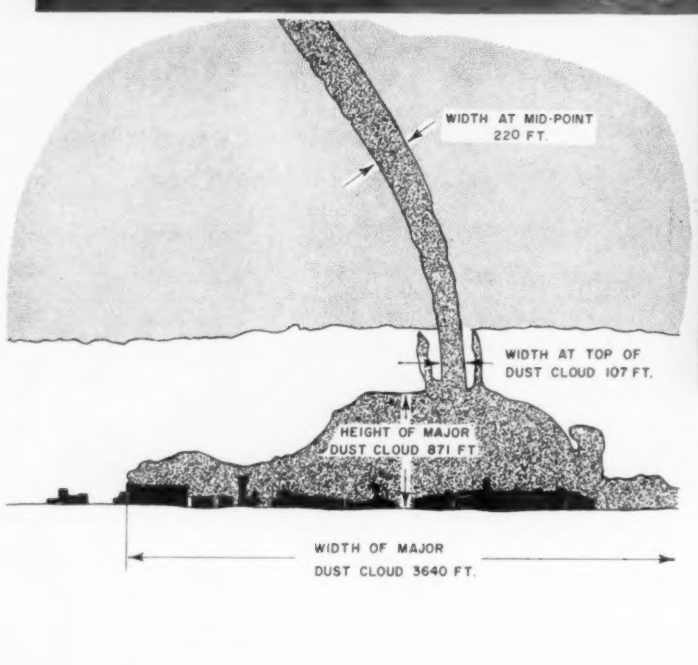

Figure 3.—Tornado funnel photographed from near Weather Bureau office at airport and after time of figure 2. Sketch shows measurements made. (See position on fig. 1 inset.)

Figure 4.—Tornado funnel seen near end of its existence from Weather Bureau office. Sketch shows measurements made. (See position on fig. 1 inset.)

distance they drove through a west gate of a cemetery intending to depart through a south gate. As fate would have it, the south gate was heavily chained and locked. Escape was cut off by the tornado moving over the west gate. The three broadcasters abandoned the mobile unit for the basement sanctuary of a stone building, but left the mobile unit in operation so that the noise of the tornado was broadcast to the public from a distance of not more than 100 feet from the very center of the tornado. This noise was a very audible roar that might be compared to many trains passing in unison. Though the automobile housing the mobile broadcasting unit was damaged to the extent of $1,200 it remained upright and the broadcasting unit continued to function through the entire period. The broadcasters in the basement or furnace room were having the experience of a lifetime. As they huddled around the furnace they observed tools, such as shovels, hoes, rakes, etc., scoot up the entrance ramp and disappear. Then came total darkness and a deepening roar. The furnace twisted and heaved and the broadcasters found it difficult to breath. Whether this was due to pressure or lack of such could not be determined. Time in this case seemed to be in minutes and over this time the temperature dropped from a mild summer value until the broadcasters were chilled until they were actually cold. The roar moved on east, light returned, and the broadcasters emerged unhurt to observe the tornado funnel in action continue a slow movement to the east as they resumed voice broadcasting describing the location and action of the tornado funnel. One observation was of large pieces of debris rotating counterclockwise in the funnel and slowly going upward and then suddenly dropping rapidly toward the ground. These large pieces would stop just short of the ground and then again rise slowly while rotating. Measurements showed the building within which they took refuge was within 100 feet of the exact center of the tornado and the building was totally covered by the funnel. The building was only slightly damaged. Other equally sturdy buildings in a relative location to the tornado path were completely destroyed. Neither the broadcasters nor the occupant of the car as reported above observed any unusual light. The static in the radio broadcast from the mobile unit did not blot out the roar of the tornado and it is not believed that it would have blanked out a voice broadcast throughout the period. Voice broadcasts directly before and after the abandonment were audible through the static.

4. PHOTOGRAPHIC MEASUREMENTS

This tornado funnel was widely photographed and it was possible to locate the exact spot from which many pictures were taken and to measure the distance from that point to the path of the tornado. By setting up a surveyor's transit at the spot from which the pictures were taken it was possible to determine the exact azimuth of the funnel and its exact location at the time of the photographs.[2] Measurements were taken of angles between landmarks shown in the pictures encompassing the tornado funnel, and thus by comparison it was possible to determine the angular width and height of the tornado funnel and the dust cloud. Thus knowing the distance to the funnel and its angular width and height it was possible to measure the width and height of the funnel and the associated dust cloud in feet. Eight pictures (pictures where the path of the funnel was not parallel to the view of the picture) were so measured.

Figure 2 is one of the scaled pictures from which measurements were taken. The view is toward west-northwest from the Scottsbluff Municipal Airport. The following values were obtained for figure 2:

Distance to the funnel=11,162 ft.
Width of the funnel=741 ft.
Height of the funnel=2,852 ft.
Width of dust cloud=5,687 ft.

For figure 3, a picture taken from the Scottsbluff Municipal Airport looking southeast, the following values were obtained:

Distance to the funnel = 11,100 ft.
Width of mid-point of funnel = 220 ft.
Width of funnel at top of dust cloud = 107 ft.
Height of major dust cloud = 871 ft.
Width of major dust cloud = 3,640 ft.

For figure 4, a picture taken from the Scottsbluff Municipal Airport looking east-southeast, the following values were obtained:

Distance to funnel = 18,850 ft.
Width of funnel just above ground = 307 ft.
Height of main cloud deck = 3,700 ft.

5. PRESSURE TRACE

Figure 5 shows the barograph trace from midnight to midnight June 27, 1955, for the Weather Bureau Office at Scottsbluff. The tornado passed one-half mile south of the barograph at 5:05 p. m., MST. The lowest point on the barograph trace was 25.890 inches and occurred 32 minutes prior to the time the tornado reached the nearest point to the barograph. At the time of the lowest barograph reading the tornado was approximately 6 miles to the west-northwest. The several interesting features of the barograph trace deserve further study.

6. RADAR PICTURES

Figures 6 and 7 show pictures taken of the echo on the radar at the Weather Bureau Office, Scottsbluff. The radar was a 10-cm. APS-2F with a 72-in. antenna. The camera used was 35mm, using a 1+ portra lens, a setting of *f*4, a focusing distance of 18 inches, and a time lapse of one sweep of the radar beam. Eight similar pictures were obtained as the tornado moved from 18 miles to

[2] Mr. D. M. Little, Deputy Chief of the Weather Bureau, suggested that these measurements be made.

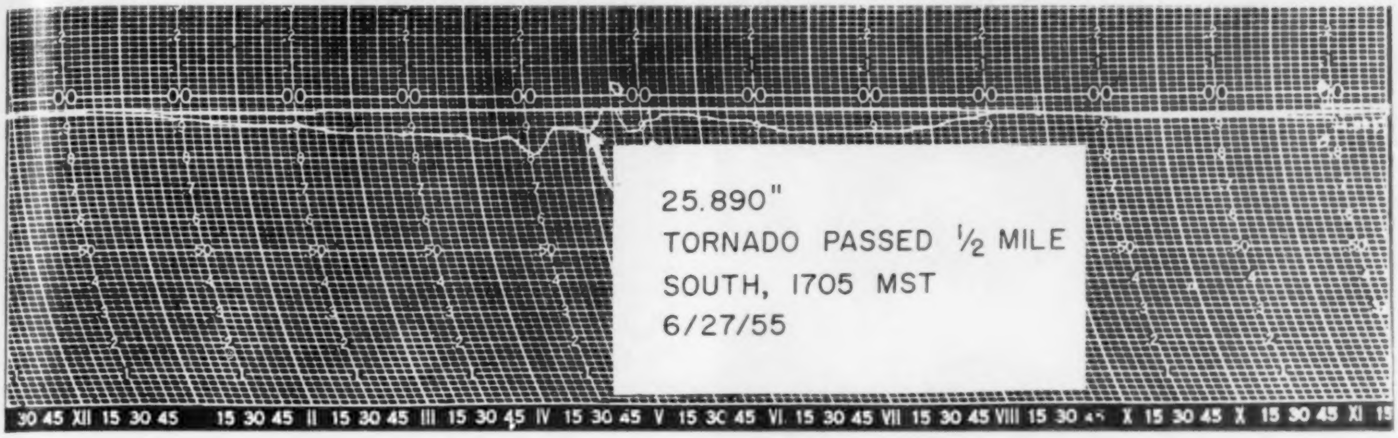

FIGURE 5.—Pressure trace at Weather Bureau office, Scottsbluff, during passage of tornado to the south.

within 2½ miles of the radar. The hook or "number 6" appearance of the cloud echo was in evidence at about 19 miles distance becoming more pronounced as the tornado came closer to the station. The tornado passed one-half mile south of the radar (see fig. 1) cutting off all power so no view of the dissipation of the tornado cloud was observed on the radar.

7. UNUSUAL GROUND MARKINGS

Figures 8 and 9 are aerial photographs of some unusual markings in a cultivated field northeast of Scottsbluff (see fig. 1) that were caused by the tornado. A heavy rain shower followed the tornado over the field and some 40 hours elapsed between the time the tornado passed and these marks were photographed. The field had been planted in potatoes and beans and at the time the cultivated soil was very loose and fine. When noted, these marks were ridges or dikes from one-fourth to one-half inch in height and were arranged in waves similar to ripples on a pond. The surface soil was impregnated with a fine gravel that was not native to the field. There could be considerable speculation as to how the tornado

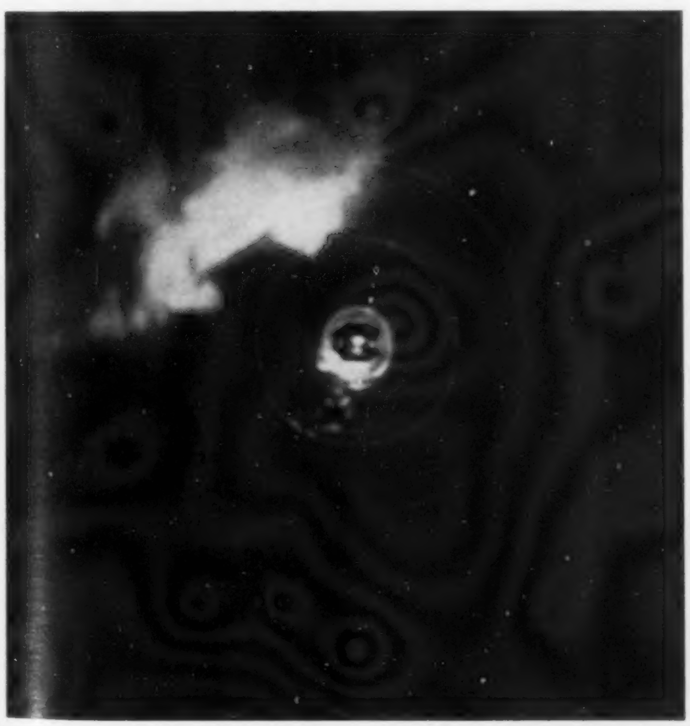

FIGURE 6.—Photograph of echo on radarscope at Weather Bureau office, 1555 MST, June 27, 1955. Range marks are at intervals of 5 nautical miles, tilt is 4.9°. Position of tornado is marked by hook-shaped echo at azimuth 288° and 14.5 nautical miles distant.

FIGURE 7.—Radar echo at 1635 MST, June 27, 1955. Tornado is at azimuth 282° and 6.0 nautical miles distant. Range marks are at intervals of 5 nautical miles, tilt is 6.4°.

FIGURE 8.—Aerial photograph of cultivated field near Scottsbluff showing elliptical markings made as the tornado passed. Note change in direction of path.

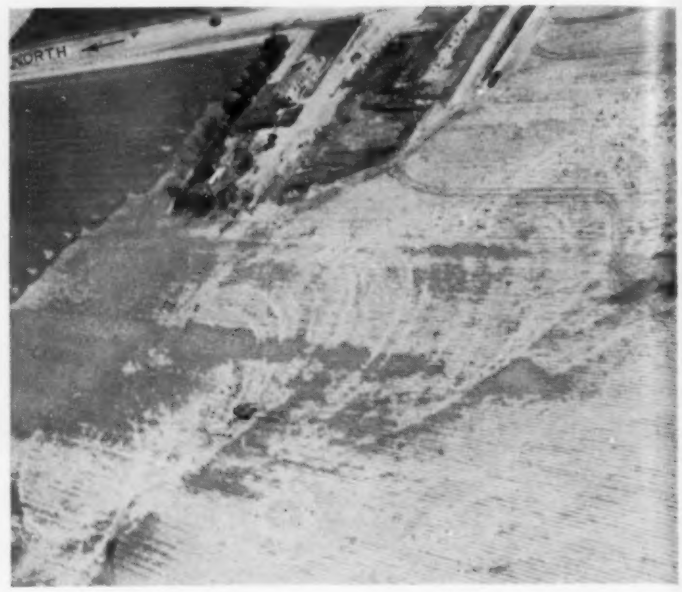

FIGURE 9.—Another view of same field as shown in figure 8.

produced these marks. That is left to the imagination of the reader.

A ground survey did not show a pattern in the markings for obtaining measurements. However, the pictures show systematic markings and the field was measured in order that the pictures could be scaled. Apparently these markings form a near ellipse. In the following computations it is assumed they are a true ellipse. The forward speed of the tornado cloud cell as determined by the radar gave an estimated forward speed of the tornado of 12 m. p. h. From the scaled photographs it was determined that the diameter of the major axis of the ellipse was 230 feet and the diameter of the minor axis was 152 feet. By averaging distances between rings at the center of the leading edge over as nearly a uniform portion of the markings as possible it was determined that this average distance between markings was 15 feet 4 inches. Assuming the marking to have been made by something being carried with the speed of the revolving wind within the tornado funnel, the wind speed was determined from the relationship

$$V=CNS$$

where V is wind speed

$C=2\pi\sqrt{(a^2+b^2)/2}$ is approximate circumference of an ellipse

N is number of rings per unit distance

S is forward speed of the tornado

a is one-half the major axis of an ellipse

b is one-half the minor axis of an ellipse

With this relationship the numerical values from the scaled photographs give $V=484$ m. p. h. for the speed of the wind in the tornado funnel. It is emphasized that this result is based on an estimated forward speed and on the unconfirmed assumption that the elliptical markings were made by an object that made exactly one revolution about the vortex for each marking.

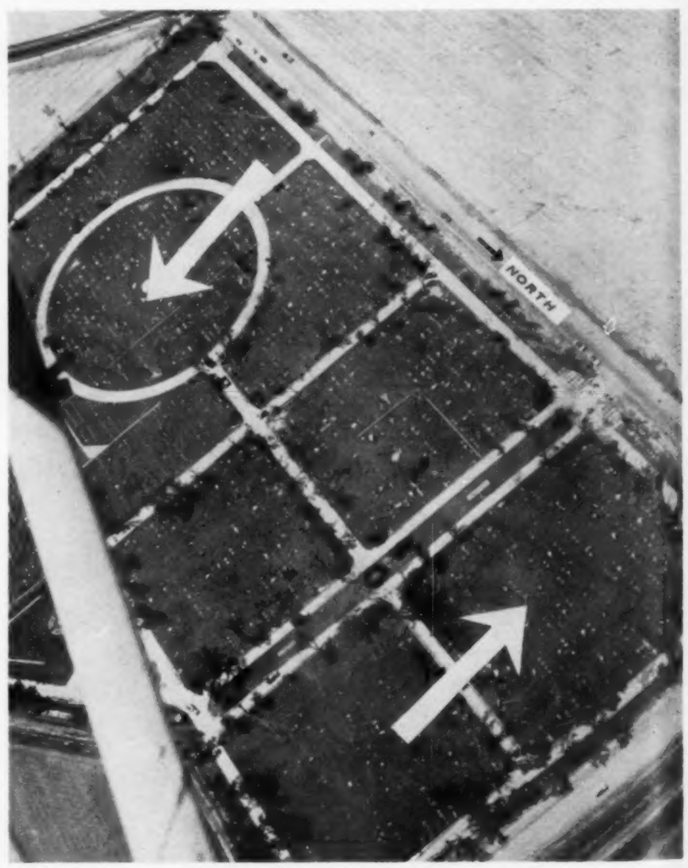

FIGURE 10.—Aerial view of cemetery showing direction in which grave markers were felled. Trees also show rotation in their different directions of fall.

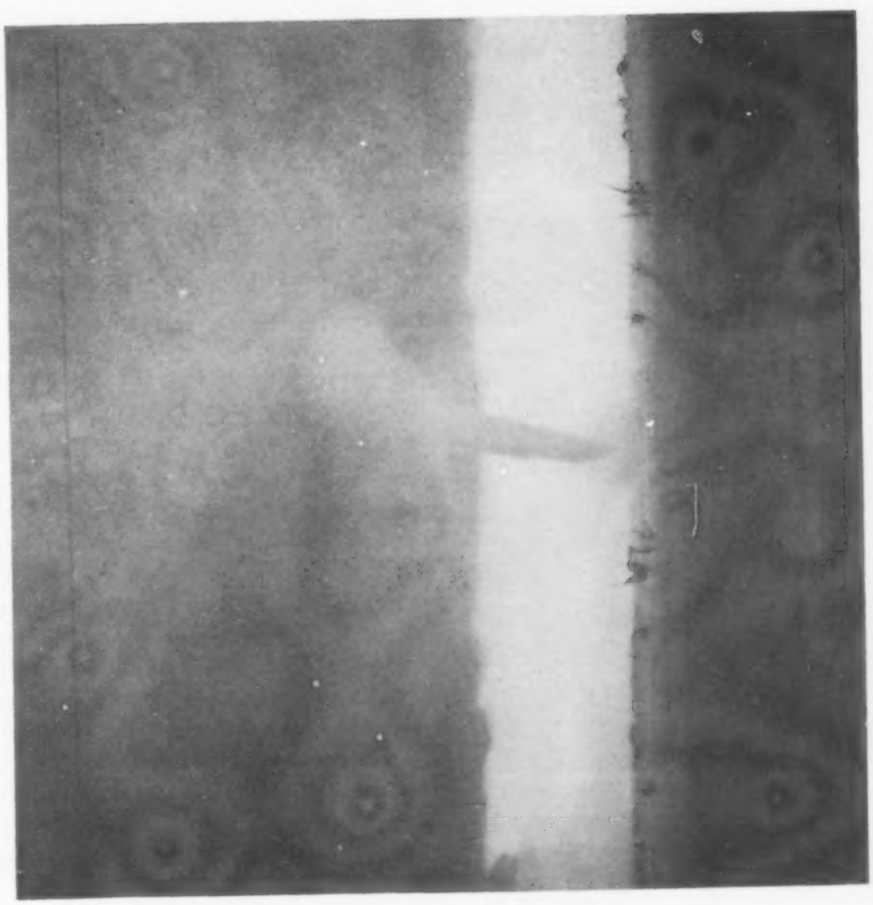

FIGURE 11.—Tornado near Mitchell showing the funnel shape of the protuberance.

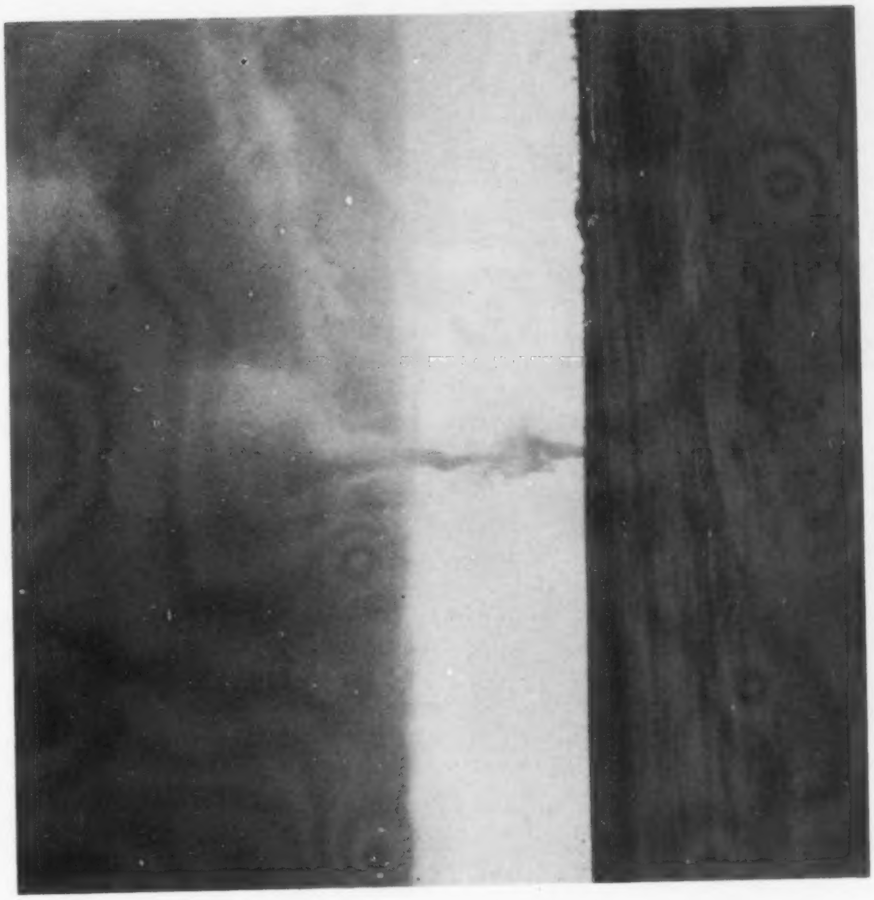

FIGURE 12.—Dust cloud rising to meet funnel in Mitchell area.

Not only did the motion of the funnel's contact with the ground vary from side to side, but as shown by sequence pictures the lower part of the funnel both ran ahead and trailed behind the upper part of the funnel. Whether or not this was because of a backward movement of the lower part of the funnel or because the lower part remained stationary until the upper part passed is not shown by the still photographs. The 90° bend in the markings in the field as shown in figure 8 is evidence of a sudden change in direction of the lower part of the funnel. The stairstep line of the tornado path near Scottsbluff as shown in figure 1 is an indication of abrupt direction changes.

8. DOWNDRAFTS

There were three reliable reports of severe downdrafts on the south side of the tornado. An observer a short distance south of Henry reported he could see a dark cloud in the sky but no funnel. He experienced surging blasts of wind that seemed to drive his car into the ground. An almost identical occurrence was reported four miles south of Morrill. One of the meteorologists at the Scottsbluff Weather Bureau Office who was driving his car on the highway a few hundred feet south of the tornado funnel as it passed 2½ miles east of Scottsbluff observed cold downdrafts that actually bounced his car up and down. Shortly after the passage of the tornado the writer observed sticks and shingles that had been driven into the ground by the tornado at about a 60° angle with the tops leaning northwest. These were in the vicinity where the Weather Bureau meteorologist observed the cold downdrafts. Outside the tornado funnel on the north side winds were comparatively light. At the Weather Bureau Office, one-half mile north of the tornado, the maximum wind speed was 30 m. p. h. On the south side of the tornado winds were estimated at 50 m. p. h. for a distance of 8 miles.

9. WIND ROTATION

There was evidence that the winds within the funnel were rotating counterclockwise. The writer observed distinct cloud movement to that effect. West of Morrill the tornado funnel had the appearance of a large whirlwind and several observers reported that debris could be seen circulating to the left. The statement by the person injured in the automobile and the observations by the radio broadcasters support the counterclockwise evidence. Further evidence of the counterclockwise movement is shown in figure 10. As indicated by the arrows in this picture the grave markers on the north side of the cemetery were toppled to the west and the markers on the south side were toppled to the east; in a strip through the middle, for a width of approximately 50 yards, the markers were not disturbed. The tornado passed from west to east through the cemetery and the wide facings of the markers face east and west while the narrow portions face north and south. Many of the markers toppled weighed over 3,000 pounds. The trees on the north side of the cemetery were felled to the west and on the south side to the east.

10. SHAPE OF PROTUBERANCE

This was perhaps the most photographed tornado occurrence in history. Forty-eight funnel photographs were collected and studied. These pictures, which ranged over a distance of 23 miles show that from near the Wyoming State line to just north of Scottsbluff the protuberance was actually funnel shaped, that is wider at the base of the cloud than at the lower extremities. Figures 11 and 12 taken in the Mitchell area show this funnel shape. From just northeast of Scottsbluff to the tornado's dissipation, photographs show the protuberance was post shaped or the same size through its full length. Figures 2, 3, and 4 were taken when the tornado was north or east of Scottsbluff toward the end of its history.

Figure 12 indicates a dust cloud rising to meet the funnel from the cloud. Several of the photographs studied showed similar situations. Some showed the dust cloud on the ground with a clear space between the dust cloud and the funnel above. In others it appeared that the funnel was touching the ground with a portion of the funnel near its midpoint removed.

11. WEATHER CONDITIONS

The tornado situation of June 27 fol'owed torrential rains of June 26 in eastern Wyoming and western Nebraska. On the afternoon and night of June 26 rains of 2 to 6 inches caused severe flash flooding for a considerable distance along the Platte Valley in eastern Wyoming and for about 8 miles into western Nebraska. The weather the morning of June 27 was generally fair. There were scattered to broken stratocumulus clouds at 2,500 to 4,000 feet above the ground, winds were southeasterly 10 to 15 m. p. h., mid-afternoon temperatures near 80° F. with a dew point in the sixties. A typical swelling cumulus cloud, as indicated by the radar, began to develop in eastern Wyoming about 1230 MST moving eastward down the North Platte Valley into Nebraska and increasing in size and intensity spreading horizontally until it was approximately 20 miles north-south and 10 miles east-west. Outside this cell area there were only scattered cumulus clouds of weak to moderate intensity. The tornado was followed by a brief heavy rain shower and some hail. Rainfall amounts varied from ¼ to 1 inch over a strip about 3 miles on each side of the path of the tornado. Several reports of a "rain of mud" were received from the north side of the tornado. Evidence of the deposits of mud could be observed along the north side of the tornado path, generally within ½ mile. There were spotted patches of hail within the rain area and most of the hailstones were generally less than ¾ inch in diameter. However, in the vicinity of Mitchell a few hailstones the size of basebal's were reported to have fallen. With the rain shower the winds shifted into the west and with the ending of the rain shower behind the funnel skies cleared as the cloud cell moved or dissipated to the east.

DUST SPHERES
A REPORT ON THEIR OCCURRENCE IN SOUTHEAST ARKANSAS

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[Manuscript received May 17, 1955]

1. INTRODUCTION

As far as is known dust spheres are an unusual phenomenon. This report describes an occurrence of atmospheric dust spheres and the observations made of them. Physical description and measurements are presented but no speculation or hypothesis regarding the origin or manner of formation of the dust spheres is attempted.

2. HOW AND WHERE OBSERVED

The dust spheres were trapped entirely by accident, incidentally to the study of air-borne pine pollens at the Crossett Experimental Forest, a Branch of the Southern Forest Experiment Station. Specifically, the dust was caught 6 miles south of Crossett, Ark., at approximately 33° N. latitude and 92° W. longitude.

Two pollen traps were used, which consisted of standard microscope slides on which were affixed strips of cellophane scotch tape with the sticky surface facing upward. One slide was placed in an open field which allowed full sweep of the wind and the other was located in a grove of large pine trees where wind movement was greatly reduced. Both slides were exposed concurrently beginning at 7:45 a. m., April 1, 1955, and ending 9:00 a. m., April 3, 1955.

Weather conditions are recorded daily by instruments in place on the station grounds. Between 3:00 a. m. and 7:00 a. m. on April 1, 0.44 inch of rain was recorded. The traps were exposed three-quarters of an hour after precipitation ceased. On April 1 the sky was cloudy; maximum temperature was 74° F., and minimum was 51° F. An 8-m. p. h. wind blew from the southwest. On April 2 the sky was partly cloudy; temperatures ranged from 71° F. to 41° F. The wind was from the north at about 4 m. p. h. It was generally noted that the atmosphere was heavily laden with dust on the night of April 1 and most of the day on April 2.

The pollen traps were examined with a microscope at 9 a. m. on April 3. Examination was first made of the slide exposed in the open site. It was noted that many concentrated patches of small particles of what appeared to be silica, silt, or both, were present on the slide. Because dust is normally distributed uniformly, the presence of dust patches seemed unique. These patches or "splashes" are shown in the photomicrograph in figure 1. Examination of the slide exposed in the pine tree grove disclosed the presence of opaque, rough-textured spheres of unknown identity. These are illustrated in figure 2. When touched with a dissecting needle the spheres shattered readily, forming concentrated patches of small particles similar to those observed on the first slide. The spheres, now clearly identified as composite dust bodies, were found to be made of particles identical in appearance to those observed in the dust patches on the first slide examined. Thus, the presence of the dust spheres explained the formation of the concentrated dust patches.

It is believed that there were no dust spheres on the slide exposed in the open situation because the unobstructed wind currents caused the spheres to strike the slide with sufficient force to shatter them. By the same token the pine tree grove slowed the wind currents suffi-

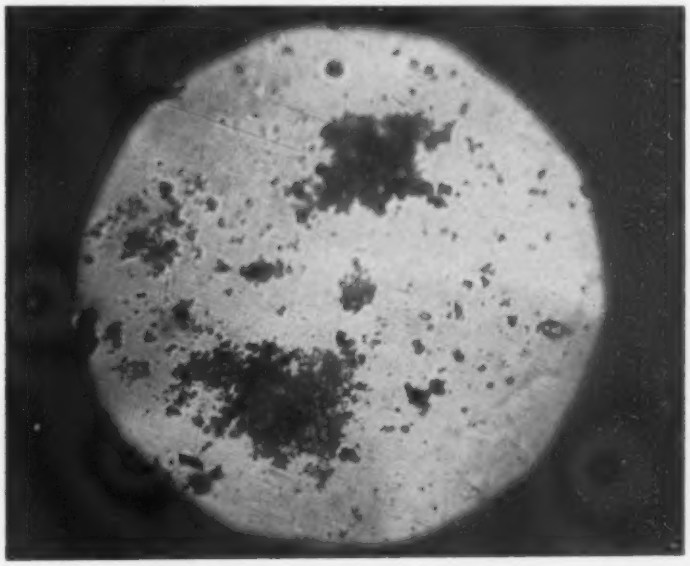

FIGURE 1.—Typical concentrated dust particle patches formed by atmospheric dust spheres shattering on impact with the slide surface.

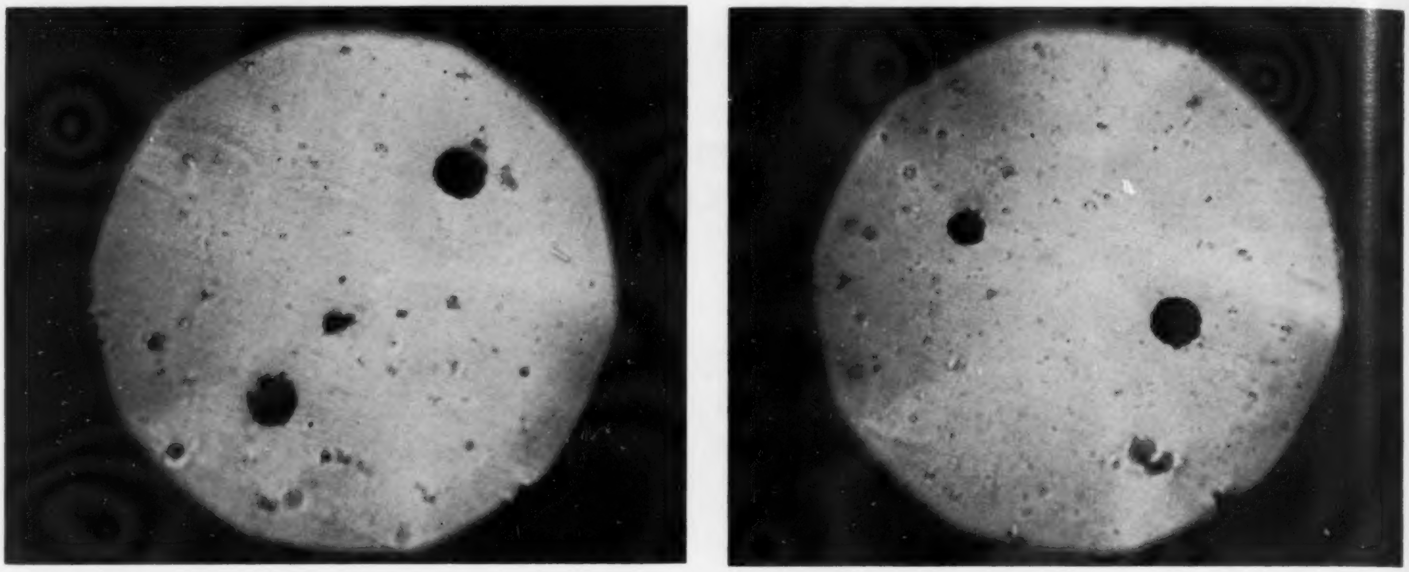

FIGURE 2.—Examples of opaque, rough-textured atmospheric dust spheres.

ciently to permit the dust spheres to settle on the slide gently and intact.

3. PHYSICAL CHARACTERISTICS

Twenty dust spheres and as many dust patches were measured. Averages and extremes are given in the following table.

	Dimensions in mm.		
	Maximum	*Minimum*	*Average*
Dust sphere diameters	0.066	0.028	0.053
Dust patch widths	.406	.084	.170
Dust patch lengths	.462	.112	.234

The very largest individual particles making up the biggest dust spheres average 0.022 mm. in length and 0.015 mm. in width. Only one or two particles of this size occur in even the biggest spheres. Most particles are extremely small in relation to sphere size and it is believed that some are so minute as to be beyond the limits of resolution of an optical microscope. For this reason the average number of particles per sphere of a given size could not be determined.

Dust patch distribution per square mm. of slide surface averages 0.8. Dust spheres average 1.4 per square mm.

AN APPRAISAL OF DIFFERENTIAL TEMPERATURE ADVECTION AND MOISTURE AS A FORECASTER OF HEAVY RAINFALL

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Manuscript received August 2, 1955; revised October 20, 1955

ABSTRACT

A series of 78 daily forecasts using differential temperature advection and moisture as a predictor of heavy rainfall is verified. The evaluation indicates that the method has some skill in detecting winter days on which to expect heavy rain, and where it will occur. A breakdown by amounts shows that the heavier the rainfall, the greater the probability of its occurrence being forecast and the greater the accuracy in the placement of the rainfall center.

1. INTRODUCTION

The problem of the prediction of heavy precipitation is one of the most difficult in the science of meteorology. It is at the same time one of vital importance for river forecasting and flood control operations. As a part of its function, the Hydrometeorological Section of the Division of Hydrologic Services of the Weather Bureau has made several approaches to the problem, one of which will be appraised here. This paper reports the results of a test of Gilman's [1] concept of differential temperature advection as a cause of vertical motions in the atmosphere leading to heavy rainfall if sufficient moisture is present.

2. THE TEST

During the period from October 26, 1953, to March 1, 1954, inclusive, a series of 78 daily forecasts of heavy rainfall was made in the Hydrometeorological Section. The forecasts were made Monday through Friday of each week except for the period December 24, 1953, to January 3, 1954.

A detailed account of the method used in arriving at the forecast has been presented by Appleby [2]. Briefly, the method consists of advecting the isotherms and dewpoint lines on the 850-mb. chart by means of forecast air trajectories. A grid is then placed over the chart and the present and future temperatures read off. Temperature changes are computed at the grid points. The Laplacian of these forecast changes is calculated and is defined as the differential temperature advection. When areas of forecast warm differential temperature advection and high moisture overlap, heavy rain is expected.

All of the forecasts were made from the 0300 GMT 850-mb. chart for the 6-hour period, 1200–1800 GMT, the same day. The 0630 GMT surface map and the 30-hour prognostic surface map (made from 0630 GMT data), together with a certain amount of judgment, were used to forecast the movement and to some extent the change in shape of the 850-mb. features. These 0630 GMT data were the latest used.

Isolines of forecast differential advection of $-4°$ C./6 hour/° latitude/° latitude were drawn. This value was chosen on the basis of some preliminary forecasts during the early fall of 1953. Minus 4° was selected at the beginning of this test and maintained throughout the series. It may be noted however, that a value of $-2°$ C. was used by Appleby [2]. Forecast values of moisture of 10° C. and 12° C. dewpoint at the 850-mb. level were both used and the results summarized.

3. ERRORS

Errors that may enter into the calculation of the forecast parameters can be classed as follows:

(1) Errors in the prognosis of: (a) frontal positions, (b) change in shape of systems and (c) change in intensity of systems. Generally, errors of type (a) are not as serious as might be supposed. This is because the winds are used to move the isotherms and small errors in the movements of the system affect only a slight displacement of the forecast heavy rain area and usually not its existence. The errors of type (b) and (c) may be very serious. It is here that the skill of the forecaster can come into play most efficaciously.

(2) Errors in the short-cut trajectory method of moving the isotherms. This type is rather hard to assess, but some preliminary comparisons with more laborious methods of trajection show comparable results.

(3) Errors in differential advection due to non-advective temperature changes. This error was most pernicious in regard to the downwind change in the temperature field aloft caused by the formation of a rainfall area after the

[1] In cooperation with Corps of Engineers, Department of Army.

time of the upper air observations from which the forecast is made.

(4) Errors due to approximations used in the computation of the differential advection. The differential advection is computed as an average over a 6-hour period. While this is reasonable in view of the duration of heavy rains (not duration at a given point on the earth's surface), some heavy rain cases of very short duration may be missed by the averaging process.

(5) Errors in reported upper air data. This source of error is considered small.

(6) Errors in analysis of the upper air data. For the most part this error is small except for a spatial inadequacy in moisture observations. In a few situations large errors could result unless judgment is exercised in analyzing the moisture field by taking surface data into consideration.

4. VERIFICATION

It was decided that there was not enough congruity between forecast and observed areas to employ elaborate areal verification techniques for judging the results of the method. Accordingly, a simple measure, the distance between the observed and forecast areas, was used and the results summarized in a number of contingency tables (fig. 1). To show how much better than chance the forecasts were, a skill score was computed for each test using the marginal totals as climatology. The skill score measures the scheme's ability to predict the occurrence or nonoccurrence of a precipitation area of a specified intensity (or the number of precipitation areas of a specified intensity more than 100 miles apart at their periphery) within the United States east of the Rockies, except the Florida peninsula, for a given 6-hour period.

While in general the shapes of the forecast areas of differential temperature advection and the associated rain areas were not similar, there is some reason to believe that a more careful and detailed analysis would improve the correspondence. In a test of three historical situations (not part of this series) made with great care on a large scale map the correspondence of position and shape of the forecast and observed rain areas was very close. Two of these three historical cases were discussed by Appleby [2].

For rainfall verification all recording rain gage data appearing in climatological data for the United States east of the Rocky Mountains were examined. For each forecast day all significant rainfall was plotted for the period 1200–1800 GMT and isohyets drawn for values of intervals of ¼ inch.

On each day that the forecast was made it was noted whether the parameters congruently reached the following "critical" values: $\geq 10°$ C. and $\geq 12°$ C. 850-mb. dewpoint together with $-4°$ C. differential advection. If no area was formed by the overlapping of the above values the forecast was for no heavy rainfall (heavy rainfall being defined as 1 in./6 hr. and .75 in./6 hr.) in the United States east of the Rocky Mountains (except the Florida peninsula). A heavy rain "hit" was recorded when a forecast area and an observed area (of specified magnitude) occured within the United States east of the Rockies, except the Florida peninsula, no matter what the distance between them. This was done in order to avoid the use of an arbitrary criterion for success or failure of a forecast. In each case the distance between them was measured from center to center. A summary of the distances is presented in histogram form with each contingency table.

In cases where multiple rain or forecast areas were encountered, the following rules were observed: (1) When the edges of two observed heavy rain areas were within 100 miles of each other at their closest, they were counted as a single combined area. (2) Two heavy rain forecast areas were treated as two separate areas regardless of the distance between them. (3) If two heavy rain areas were forecast and two observed, each forecast area was paired with the nearer heavy rain area and this distance was recorded. (4) If one rain area was observed but two heavy rain areas were forecast, the nearer heavy rain area was paired with the forecast area and the other area was counted as a "miss". The same rule was followed with two observed heavy rain areas and one forecast area.

The verification of rainfall areas and/or forecasts near the coastline presented a difficulty. It was decided that for consistency the forecast heavy rain areas would be ignored if they occurred entirely off the coast but if they occurred partly on and partly off the coast to use only that part over land. In this way the observed and forecast areas are treated equally, although a slight bias toward reducing the verification score results. This was deemed fairer than introducing a favorable bias of unknown magnitude.

In these contingency tables the no-heavy-rain-forecast, none-observed box has only one observation per day, while the other boxes on a few days contain more than one per day. This bias was not thought to be large enough to seriously affect the judgment of the method.

5. EVALUATION

A summary of results attained by the method in the daily series is given in figure 1 and table 1. It would appear from the contingency tables (fig. 1) that a positive, though not high, skill above chance in selecting those winter days on which to expect heavy rain, was exhibited in all the tests. Test No. 1 (differential temperature advection $\leq -4°$ C.; dewpoint $\geq 10°$ C.; 6-hour rainfall ≥ 1.00 inch), which forecast heavy rain 37 times when heavy rain was observed 33, showed the highest skill score as well as the best balance. These values of the parameters should be preferred over the others when the method is used.

The median distance that was missed varied from 140 to 165 miles and probably does not represent a significant difference among the tests.

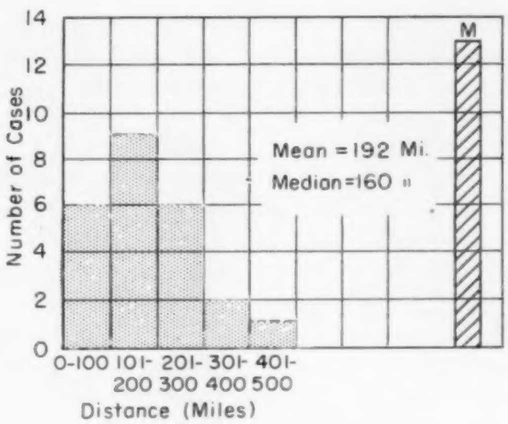
The skill scores also show the method works considerably better at forecasting rains over 1.00 inch than with rains over 0.75 inch. A further extension of this effect

Test No. 1

Forecast differential temp. advection, 850 mb. ≤ -4°C.
Forecast dew point at 850 mb. ≥ 10°C.
6-hour rainfall (1200-1800 GMT) ≥ 1.00 in.

		Forecast: Heavy rain	Forecast: No heavy rain	Total
Observed	Heavy rain	24	9	33
	No heavy rain	13	50	63
	Total	37	59	96

SS = .51
P_1 = 65
P_2 = 73

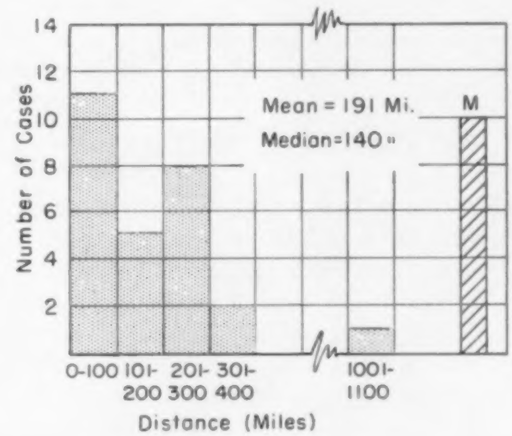


Test No. 3

Forecast differential temp. advection, 850 mb. ≤ -4°C.
Forecast dew point at 850 mb. ≥ 10°C.
6-hour rainfall (1200-1800 GMT) ≥ 0.75 in.

		Forecast: Heavy rain	Forecast: No heavy rain	Total
Observed	Heavy rain	27	20	47
	No heavy rain	10	47	57
	Total	37	67	104

SS = .41
P_1 = 73
P_2 = 57

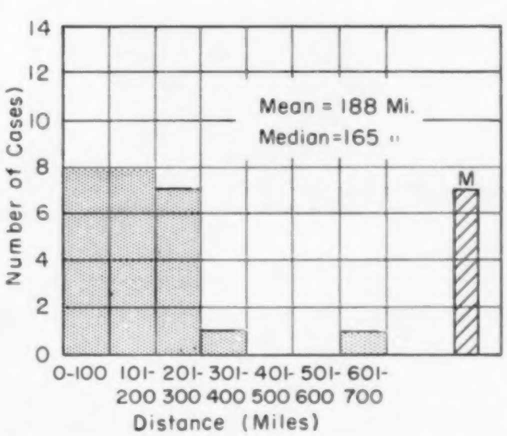


Test No. 2

Forecast differential temp. advection, 850 mb. ≤ -4°C.
Forecast dew point at 850 mb. ≥ 12°C.
6-hour rainfall (1200-1800 GMT) ≥ 1.00 in.

		Forecast: Heavy rain	Forecast: No heavy rain	Total
Observed	Heavy rain	19	14	33
	No heavy rain	7	52	59
	Total	26	66	92

SS = .48
P_1 = 73
P_2 = 58



Test No. 4

Forecast differential temp. advection, 850 mb. ≤ -4°C.
Forecast dew point at 850 mb. ≥ 12°C.
6-hour rainfall (1200-1800 GMT) ≥ 0.75 in.

		Forecast: Heavy rain	Forecast: No heavy rain	Total
Observed	Heavy rain	21	26	47
	No heavy rain	5	48	53
	Total	26	74	100

SS = .36
P_1 = 81
P_2 = 45

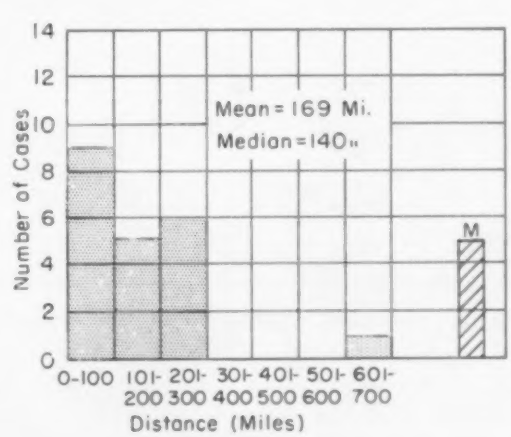


FIGURE 1.—Contingency tables for heavy rain forecasts and histograms showing distances in miles between forecast and observed heavy rain areas (shaded) and number of cases when heavy rain was forecast but not observed (*M*, hatched). *SS*=skill score, P_1=percentage of heavy rain forecast that verified, P_2=percentage of observed heavy rainfalls that were forecast.

TABLE 1.—*Cases of observed rainfall ≥ 1 inch in tests No. 1 and No. 2, categorized by rainfall intensity and mean distance between forecast and observed rain centers. P_2 = percentage correct*

	Test No. 1 850-mb. dew point ≥ 10° C.			Test No. 2 850-mb. dew point ≥ 12° C.		
Observed \ Forecast	Heavy rain	No heavy rain	Total	Heavy rain	No heavy rain	Total
Heavy rain	24	9	33	19	14	33
Intensity Breakdown (cases)						
≥3 in.	2	0	2	2	0	2
2-3	8	1	9	6	3	9
≥2	10	1	11 (P_2=91)	8	3	11 (P_2=73)
1-2	14	8	22 (P_2=57)	11	11	22 (P_2=50)
Mean Distance Breakdown (mi.)						
Heavy rain	192	(24 cases)		188	(19 cases)	
≥2 in.	162	(10 cases)		122	(8 cases)	
1-2	213	(14 cases)		236	(11 cases)	

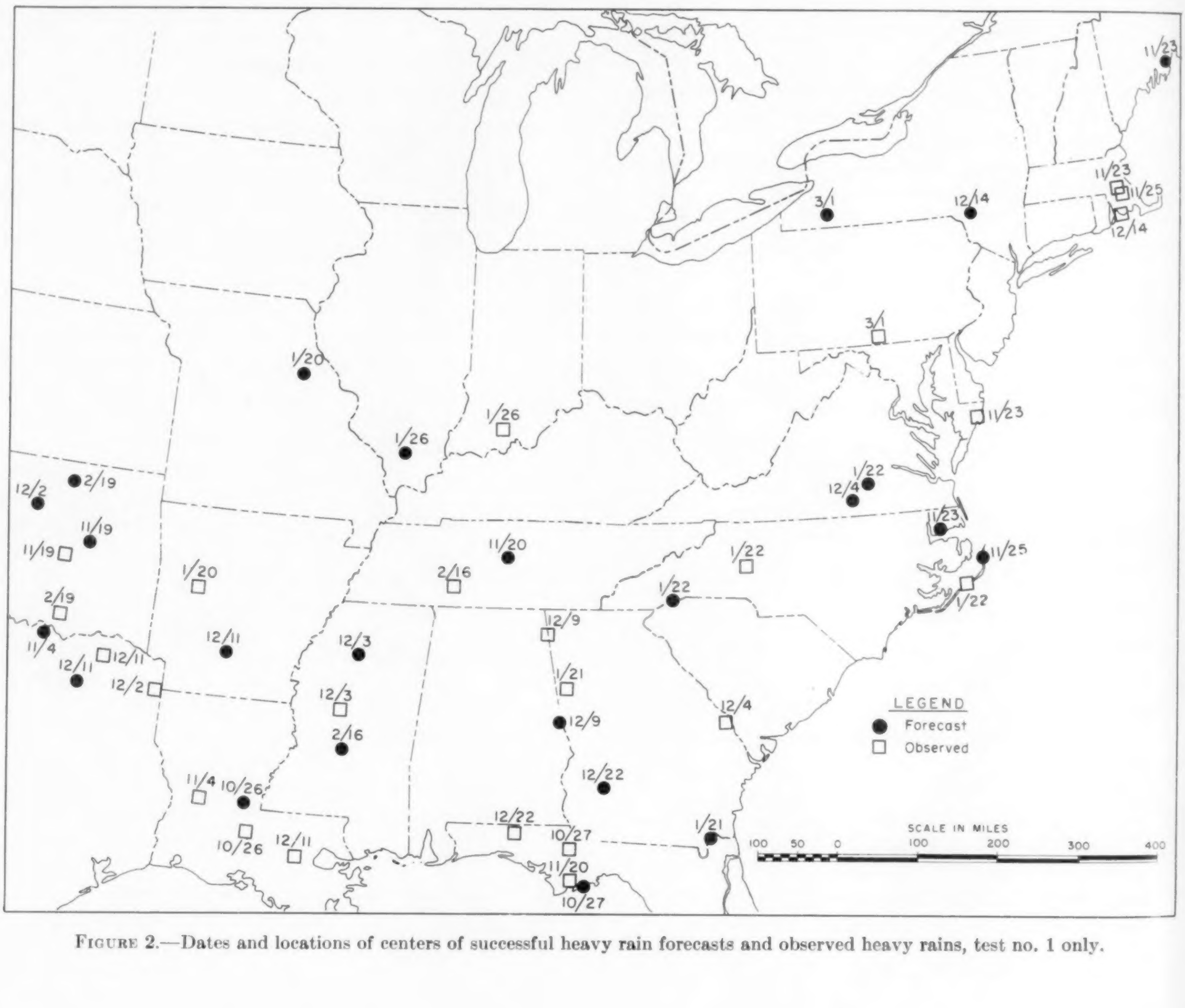


FIGURE 2.—Dates and locations of centers of successful heavy rain forecasts and observed heavy rains, test no. 1 only.

is seen in the breakdown of rains over 1.00 inch. The highest 6-hour amount recorded during the test was 3.10 inches on December 3, 1953. There were 2 cases with observed amounts above 3 inches, both of which were forecast. Table 1 shows a breakdown of the observed heavy rain cases into rainfall intensity categories.

It would appear from this breakdown that the heavier the rainfall, the more skill the method has in being able to forecast it. For example, test no. 1 (6-hour rainfall≥ 1.00 inch) P_2 has a value of 73 percent. This measure is 57 percent for rains between 1 and 2 inches but becomes 91 percent for rains over 2 inches. The average distance missed also is less. A similar trend was also found in test no. 2.

No relationship was found between the differential advection alone as measured by the present procedure and the 1–2 inch rains as differentiated from those over 2 inches.

Another way to demonstrate the skill possessed by the method was to plot the scatter of observed heavy rain "hits" (test no. 1 only). It can be seen (fig. 2) that they are fairly well distributed from the Texas-Oklahoma region to New England. A mechanical forecast of heavy rainfall was then made using the centroid of the observed heavy rainfall centers. A histogram of the resulting distances missed (fig. 3) may be compared directly to the distances missed of test no. 1 (fig. 1). It can be noted that a marked decrease is attributable to the method.

6. SUMMARY

The method reveals a certain skill in detecting those winter days on which to expect heavy rain and where it will occur. The heavier the rainfall, the greater the probability of its being picked out and the greater the accuracy in the placement of its center. It must be the decision of the prospective user, however, whether the manpower required to make the forecast is balanced by the knowledge gained.

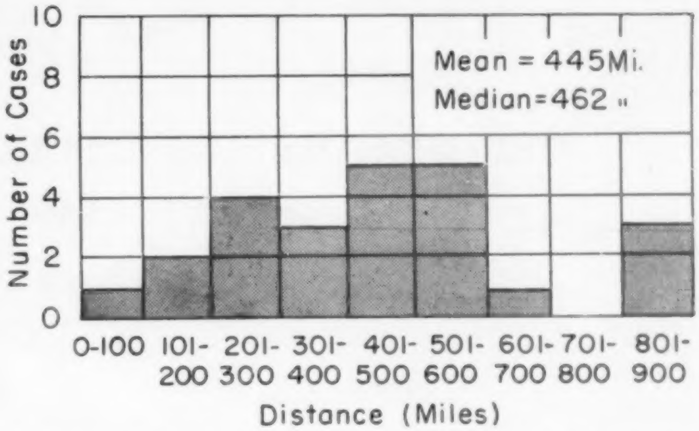


FIGURE 3.—Histogram of distances between centroid of observed heavy rains (used as a forecast) and locations of observed heavy rain.

ACKNOWLEDGMENTS

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THE WEATHER AND CIRCULATION OF NOVEMBER 1955 [1]

A Month with Pronounced Blocking and Extreme Cold

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1. INTRODUCTION

November of 1955 was unusually cold and stormy over most of the United States. Severe winter weather gripped the Northwest in particular, with blizzards bringing record-breaking cold and snow. This unusual weather was associated with a pronounced blocking regime which carried over from October [1] and indeed has been typical of this year as a whole [2].

2. TEMPERATURE DISTRIBUTION

Except for some of the Mexican Border States, unseasonably cold weather was the rule throughout the country. Repeated outbreaks of intensely cold Canadian air invaded the northern United States, and several of these were strong enough to overspread the entire nation. In the Northwest these frigid surges were sufficient to produce new record low temperatures for the month for many stations. To illustrate the extreme nature of this November's cold weather, table 1 was prepared.

For Spokane, Wash., and Billings, Mont., these figures represent new extremes of cold for the period during which records have been maintained. For most of the other stations one must go all the way back to 1896 [2] to find a colder November.

To illustrate further the extent and severity of this year's cold snap, figure 1 has been prepared to show the standardized departure from normal for the monthly mean temperature of November 1955 (Chart I). The data were compiled by dividing the observed departure from normal of this month's mean temperature by that station's standard deviation for November computed for the 30-year period 1921 through 1950 [3]. The extreme departure of −15.8° F. at Great Falls, Mont., is 3.4 standard deviations lower than the November normal. Noteworthy is the fact that Tatoosh Island, Wash., though its mean temperature was only 6.1° F. below normal, shows a standardized departure from normal almost equal to that at Great Falls. In this sense the November aberration at Tatoosh was comparable in severity and unusualness to that at Great Falls owing to much smaller variability along the coast than inland.

In considering the magnitude of this month's temperature abnormality, it may be of interest to consider probabilities of occurrence. Under the assumption of a random sample from a normally distributed population and without serial correlation from one year to the next, a standardized departure of −2.5 has a chance of occurrence of roughly one in a hundred. Thus an inspection of figure 1 reveals that over a strip covering northern Washington and Idaho, most of Montana and the Dakotas,

TABLE 1.—*Monthly mean temperature (° F.) for November 1955 at selected stations arranged in order of decreasing standardized departure from normal*

Station	Mean	Departure from normal	Standardized departure from normal	Previous minimum	
				Mean	Year
Great Falls, Mont	19.4	−15.8	−3.4	14.8	1896
Tatoosh Island, Wash	41.3	−6.1	−3.2	39.7	1896
Havre, Mont	13.7	−17.2	−3.1	3.8	1896
Miles City, Mont	19.0	−14.0	−2.8	12.7	1896
Bismarck, N. Dak	15.1	−13.3	−2.8	7.2	1896
Valentine, Nebr	26.0	−9.3	−2.7	19.2	1896
Helena, Mont	19.7	−12.0	−2.7	18.3	1896
Huron, S. Dak	22.5	−10.0	−2.6	13.6	1896
North Platte, Nebr	29.3	−7.5	−2.6	28.2	1919
Rapid City, S. Dak	24.8	−10.5	−2.6	20.9	1896
Billings, Mont	*24.1	−11.7	−2.5	26.6	1897
Seattle, Wash	41.3	−5.7	−2.5	38.6	1896
Spokane, Wash	*28.1	−7.6	−2.5	30.6	1896

*New record.

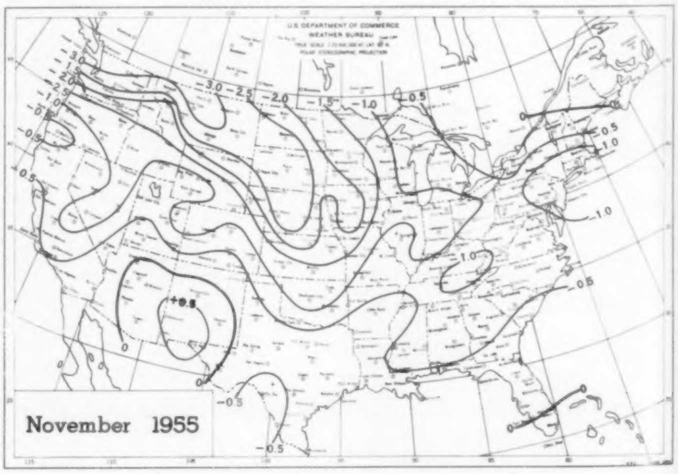

FIGURE 1.—Standardized departures from normal of monthly mean temperatures for November 1955. Average temperatures along the Canadian border of the northwestern States were more than 3 standard deviations below normal.

[1] See Charts I-XV following p. 291 for analyzed climatological data for the month.

[2] For an interesting account of the extreme weather of that unusual November, see *Monthly Weather Review*, vol. 24, No. 11, November 1896.

and northern Nebraska, a November as severe as this one has an extremely low probability of occurring by chance.

The new records of minimum temperatures for the month which resulted from the intense polar outbreaks were even more spectacular. At Helena, Mont., for example, the temperature dropped to a minimum of −29° F. on November 15, a full 7° below the previous November extreme of −22° set in 1896. Similarly, Salt Lake City suffered a minimum of −14° on the 16th as compared with a previous November low of 0° in 1931, and Missoula, Mont. recorded −23° on the 16th as compared to −11° in 1919. Some other new minimum temperature records for November are: Kalispell, Mont., −14°; Rapid City, S. Dak., −14°; Lewiston, Idaho, −3°; and Tatoosh Island, Wash., 19°. In addition, numerous previous records for minimum temperatures on individual days were broken at most stations throughout the Northwest. For comparison a few of these are listed in table 2.

TABLE 2.—*New records of daily minimum temperature (° F.) set during November 1955*

	Minimum	Date
Havre, Mont	−26	17
Great Falls, Mont	−23	13
Glasgow, Mont	−21	13
Billings, Mont	−14	14
Pocatello, Idaho	−13	16
Casper, Wyo	−12	15
Winnemucca, Nev	−5	15
Denver, Colo	−4	15
Seattle, Wash	13	15

Most of these records followed an intense storm of near-blizzard proportions which developed over the Great Basin and remained nearly stationary for several days. In addition to the extreme cold, the situation was further aggravated by heavy drifting snow. (For further details on this storm see article by O'Connor in this issue.)

One other record-breaking aspect of this cold spell was its duration. The report from Helena, Mont., that temperatures remained at subzero levels over a snow covered surface for 138 consecutive hours from the 11th to the 17th (longest such period on record) was typical of reports from most other stations in that area. New record daily minima were set each day from the 11th through the 17th at Seattle and from the 14th through the 17th at Salt Lake City. Similar statements could be made of most other stations in the northwest quarter of the country.

Figure 2 presents a broader view of the temperature distribution during this period. Of interest is the sharp south-to-north temperature anomaly gradient in the central part of the country. Thus, at the same time record minima were being set in the Northwest new record high temperatures occurred on the 16th at Charlotte, N. C. (82° F.) and St. Louis, Mo. (81°).

Of some interest is the fact that much milder weather prevailed over the northern Rockies during the previous month [1], so that November's intense cold constituted a

FIGURE 2.—Departure of average temperature from normal for the week ending at midnight, l. s. t., November 20, 1955. Shaded areas are normal or above. Dotted line indicates southern limit of freezing temperatures, dashed line, southern limit of 0° F. Note extremely cold weather in the Northwest and contrasting warmth in the Southeast. (From *Weekly Weather and Crop Bulletin, National Summary*, vol. XLII, No. 41, Nov. 21, 1955.)

sharp reversal from October. This tendency is in line with the findings of Namias [4] and has been discussed by several writers of previous November articles of this series [5, 6, 7, 8]. In this particular November, however, the tendency for reversal was characteristic only of the northern half of the country, whereas the southern half, and particularly the Southeast, saw the anomaly regime of October persist into this month.

3. TEMPERATURE AND CIRCULATION

There are several interesting aspects of the interrelationship between the observed temperature anomaly and the associated circulation pattern. While the blocking regime will be treated further in section 5, it is appropriately mentioned at this point since, as usual, it exerted a major controlling influence over the circulation pattern and served to displace the westerlies and associated cold air well south of normal.

However, aside from this general observation, it is not immediately apparent from examination of figure 3 why the cold wave should have been so intense. In fact, objective estimates based on this figure would not call for the cold to be as extensive or severe. One reason for this discrepancy is to be found in the fact that the Canadian source region for the Pc air was considerably colder than normal. Figure 4 depicts the observed distribution of thickness anomaly from surface to 700 mb. for the month. It is evident that the area of extreme cold was not confined to the northwestern United States but covered the whole extent of the Canadian Rockies. Thus, the Canadian air which repeatedly swept into the United States during the month was abnormally cold at its source, and therefore temperatures over the United States were appreciably lower than would be expected from the observed circulation alone. It is also pertinent that the center of anomalously cold air could be traced steadily southeast-

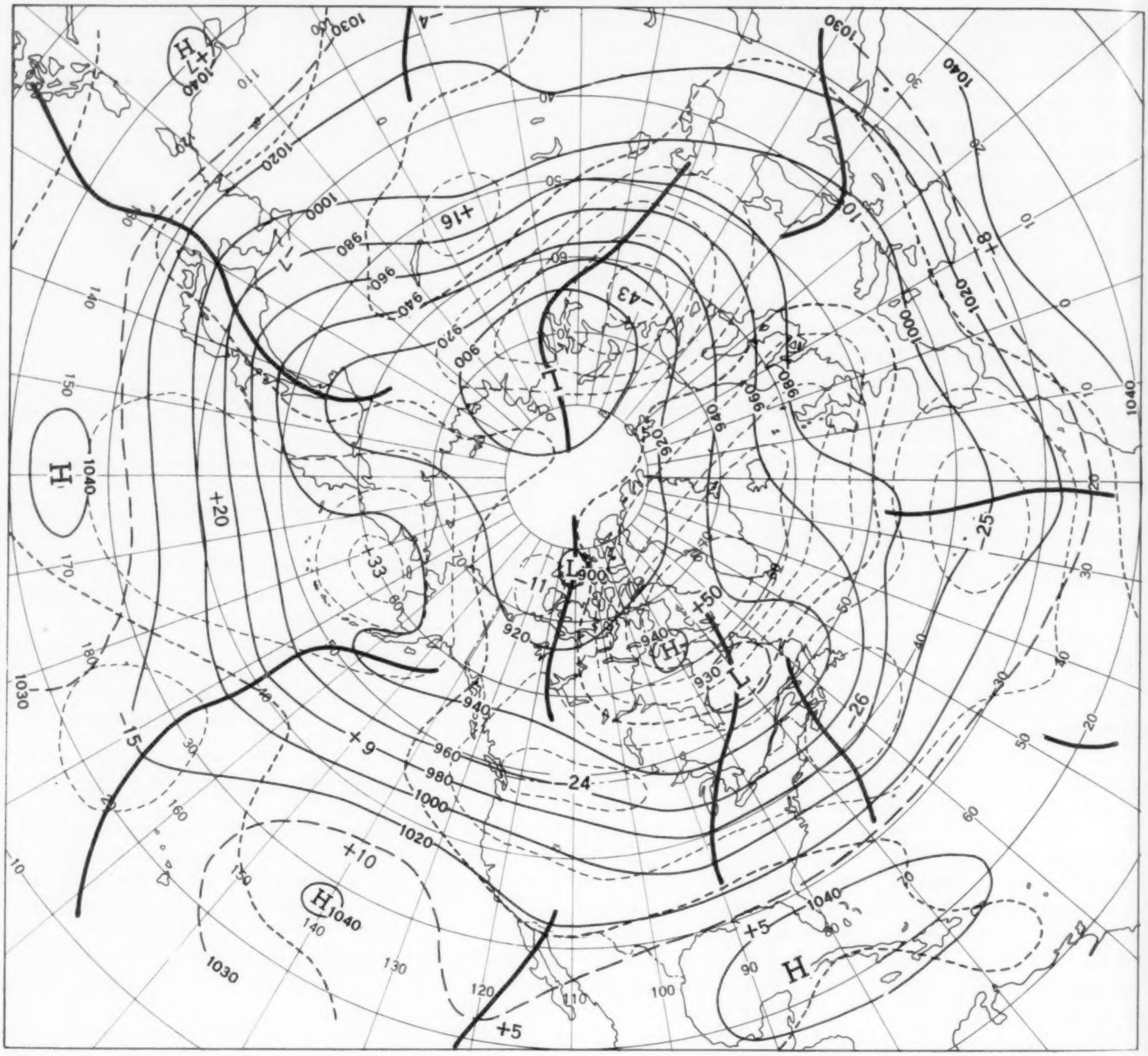

FIGURE 3.—Mean 700-mb. height contours and departures from normal (both in tens of feet) for November 1–30, 1955. Blocking was prevalent over the Davis Strait and Bering Sea, as evidenced by large centers of positive anomaly in those regions. As a result the westerlies were shifted south of normal, but with speeds greater than normal.

ward from the Arctic coast of Alaska on the mid-October—mid-November monthly mean chart to northern Montana on the mid-November—mid-December chart. This suggests that anomalous northwesterly flow over Alaska (fig. 3) was instrumental in pouring cold Arctic air into northwestern Canada. The marked effect of abnormally cold air in northwestern Canada upon temperatures in the United States has been discussed in several previous articles [5, 9, 10].

4. OTHER ASPECTS OF THE GENERAL CIRCULATION

As is readily apparent from figure 5, the 700-mb. zonal index as averaged from 5-day mean maps remained well below normal for the entire month of November, but with a general trend toward recovery from the very low value which climaxed the violent fluctuations of October described by Dunn [1]. In fact, the zonal index of 5.0 computed from the 5-day mean map of October 29–November 2 is the next lowest value observed in October or November (lowest 3.3, Nov. 25–29, 1950) in the 12 years these figures have been calculated.

The magnitude of this aberration for the hemisphere as a whole is well depicted by figure 6 which compares the mean sea level pressure profile with the normal profile for the month. Noteworthy is the very large excess of mass north of 50° N. and the compensating deficit farther south.

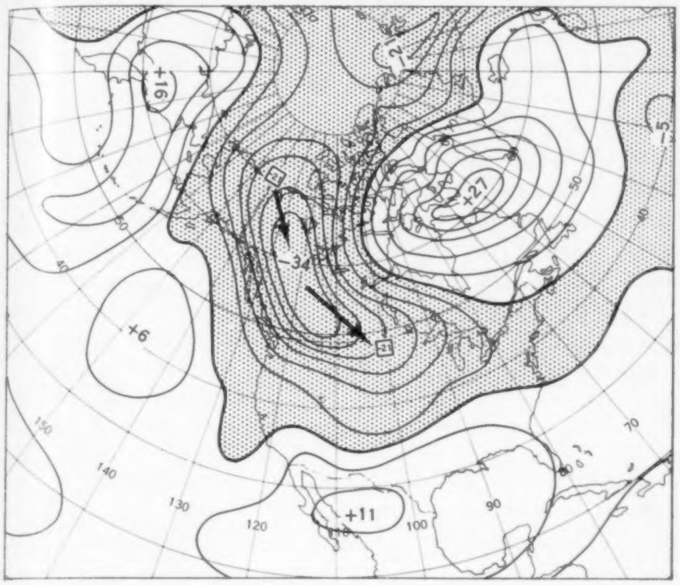

FIGURE 4.—Mean departure from normal of thickness (700 mb.-1,000 mb.) for November 1–30, 1955, analyzed for intervals of 50 ft. with centers labeled in tens of feet. Below normal thickness (shaded) covered most of the United States, with center of −340 ft. corresponding to a mean virtual temperature of about 11° C. below normal. Note warmth of blocking High over northeastern Canada and over Bering Sea with centers 9° C. (270 ft.) and 5° C. (160 ft.) respectively, above normal.

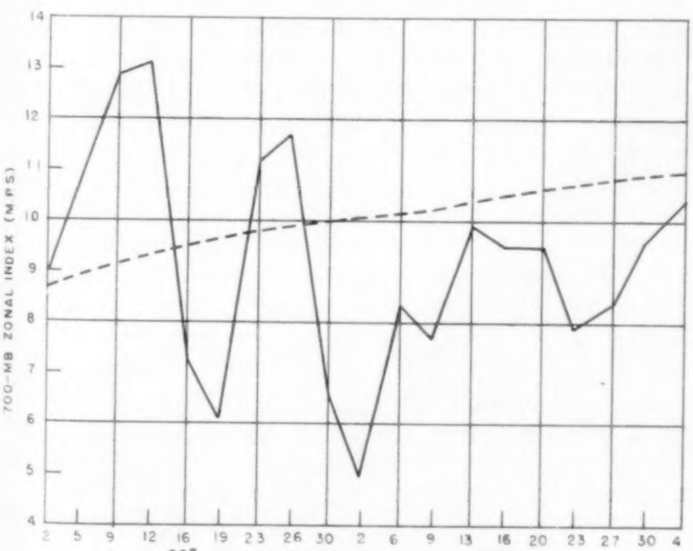

FIGURE 5.—March of 5-day mean zonal index at 700-mb. for the Western Hemisphere in the latitude belt 35°–55° N. during October and November 1955, with normal index dashed. Note that, following the very low value of 5.0 m. p. s. for the period October 29–November 2, the index remained below normal for the entire month.

An additional diagram typical of the low index state is the zonal wind speed profile shown in figure 7. It is evident that the latitude of strongest wind was displaced equatorward, with a secondary maximum appearing in polar regions and below normal speeds from 45° N. northward to about 65° N.

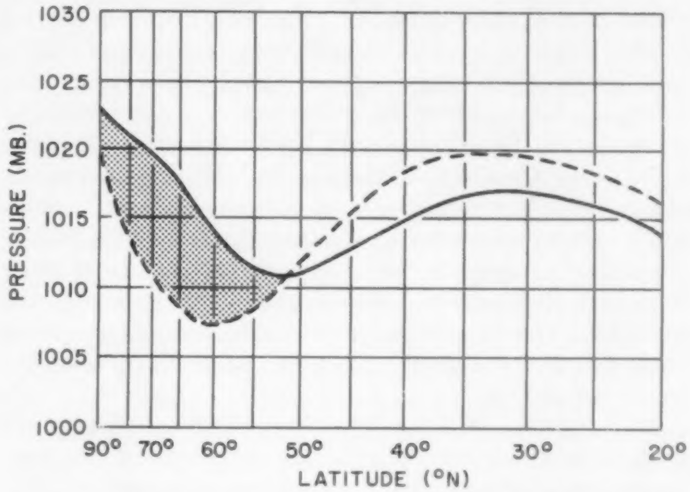

FIGURE 6.—Mean sea level pressure profile in the Western Hemisphere for November 1955 with normal profile dashed. Excess of pressure in northerly latitudes was offset by deficit to the south.

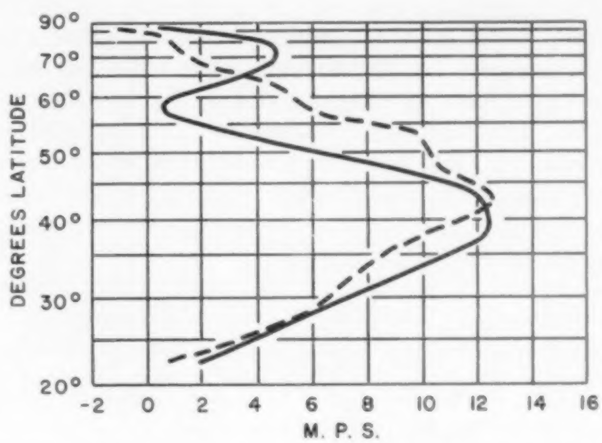

FIGURE 7.—Mean 700-mb. zonal wind speed profile in the Western Hemisphere for November 1955, with normal profile dashed and area of positive anomaly shaded. The west wind maximum was stronger and farther south than normal. Note tendency for secondary jet in polar latitudes.

A similar distribution was evident at 200 mb. (fig. 8), where a remarkable belt of subnormal winds extended throughout the Western Hemisphere roughly paralleling 55° N. The jet stream, on the other hand, was well to the south over the Atlantic with its axis extending from Hatteras to West Africa. Over the Pacific, however, the principal jet stream was farther north and corresponded more closely to its usual latitude, but with a secondary jet just north of the Hawaiian Islands.

5. THE BLOCKING

ATLANTIC

The circulation features described above resulted from pronounced blocking which was influential in controlling the Western Hemisphere circulation for October [1] and continued strongly through November. The most conspicuous center of blocking was located in the Davis Strait (fig. 3) where 700-mb. heights as much as 500 ft.

above normal were observed. The belt of above normal heights associated with this center covered a large region from northeastern Canada across the northern Atlantic to Europe. As a result of this block not one storm proceeded along the usual track across the North Atlantic to Iceland. There was considerable stalling and looping of centers along the Atlantic Seaboard as Lows were forced northward or northeastward to dissipate in the Davis Strait. Since 700-mb. heights were markedly below normal along the northern border but above normal to the south, the westerlies, though shifted southward, were faster than normal over the United States and particularly over the Southeast (fig. 3).

An inspection of 5-day mean 700-mb. height departure from normal charts reveals that two strong blocking surges proceeded westward from Europe to make up the anomaly center over the Davis Strait. The first surge came out of Europe in late October and became entrenched in Davis Strait with a maximum intensity of +1,000 ft. on the mean map for October 29–November 2. It contributed to the minimum index for that period shown on figure 5. This general locale remained the seat of rather pronounced blocking during the first half of the month. The blocking weakened around the third week of the month, only to be replaced thereafter by a second strong surge from the Atlantic. In this case maximum intensity of +940 ft. was reached in the northeastern Atlantic on the mean map for November 19–23. This block worked its way westward to exert a strong influence on northeastern Canada by the end of the month.

The broad band of above normal 700-mb. heights in the North Atlantic was associated with a belt of subnormal heights to its south. The two separate centers of negative anomaly in figure 3 reflect the variation in the blocking regime from the first half month to the last. During the former period, when the blocking was principally active over the Davis Strait, an intense, extensive, and persistent cyclone developed in the eastern Atlantic. In the latter half month, on the other hand, with blocking mainly concentrated in the northeastern Atlantic, a similar broad intense Low developed southeast of Newfoundland. Sixty-foot waves and 82-m. p. h. winds associated with the peak intensity of this storm resulted in considerable damage to the "Texas tower" radar "island" under construction off New England.

PACIFIC

Blocking was also active in the Pacific sector as evidenced by the mean ridge in the Bering Sea, which replaced the mean Low normally found in that area. This block was not as extensive nor as strong as its Atlantic counterpart, but it did achieve a positive anomaly value of 330 ft. for the month (fig. 3). Furthermore it was not as effective in producing negative anomalies to its immediate south as was the case with the stronger Davis Strait cell. In fact, above normal heights prevailed over the bulk of the Pacific, with only one center of negative anomaly showing on the mean 700-mb. chart for the month, and that was well to the south in tropical latitudes just northwest of the Hawaiian Islands. The blocking was instrumental, however, in deflecting several storms from their more usual course across the northeastern Pacific (Chart X). Some of these plunged into the western United States (fig. 9) and subjected that area to the cold stormy weather previously described.

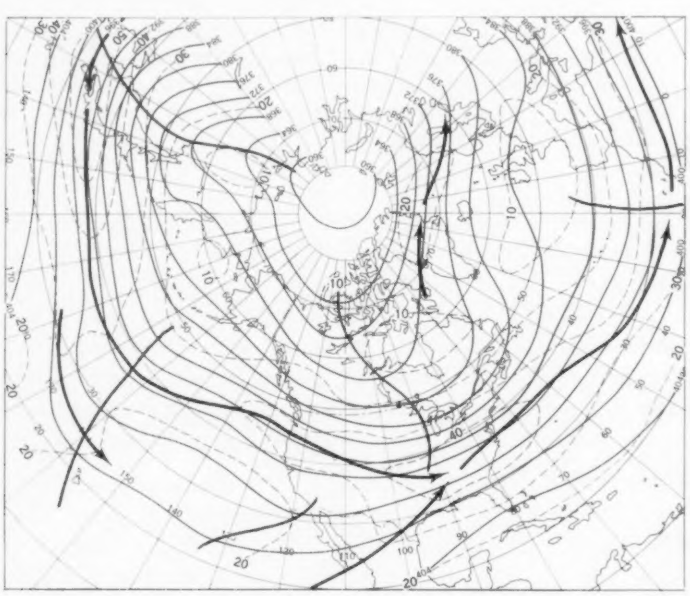

FIGURE 8.—Mean 200-mb. contours (in hundreds of feet) and isotachs (in meters per second) for November 1–30, 1955. Solid arrows indicate the position of the mean 200-mb. jet stream. Note the broad band of slow speeds along 55° N. and the weak secondary jet near the Hawaiian Islands.

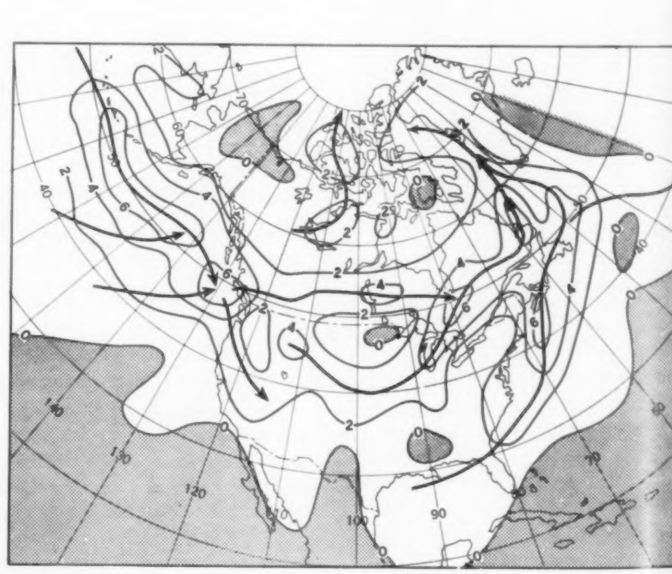

FIGURE 9.—Frequency of cyclone passages (within 5° squares at 45° N.) during November 1955. Note tendency of storms to plunge into the western United States and the complete absence of tracks across the northeastern Atlantic.

One interesting aspect of the history of the Pacific cell is the fact that it reached its greatest intensity over the Bering Sea (880 ft. in excess of normal) during the period October 29–November 2; simultaneously with the maximum intensity of the Davis Strait anomaly. It was this combination of two intense blocking cells which resulted in the near-record low value for the 700-mb. zonal index previously noted.

The Pacific anomaly was also composed of two marked surges. The first, mentioned above, slowly retreated to northeastern Siberia. It was in turn replaced by a vigorous new center which reached a peak intensity of +750 ft. above normal in the eastern Aleutians on the mean map for November 9–13. It was the strong ridge in the Gulf of Alaska associated with this anomaly which was responsible for deploying the intensely cold air from the Canadian Rockies into the western United States. It maintained strongly over the east-central Pacific and Aleutians during the latter half month and finally retrograded into the Bering Sea and weakened.

6. PRECIPITATION

As might be expected with many storm tracks displaced from Canada into the United States by the low index circulation, precipitation over much of the country exceeded normal (Chart III). The principal exception was a large area of rain shadow over the central and southern Plains States. This was the second month of deficient moisture in that area and the dry weather coupled with the unseasonable cold caused soil to become dry and loose and susceptible to wind damage.

In direct contrast, the northern and western States received copious precipitation. Except for the Pacific coast, this occurred mainly as snow and many localities in the northern Border States west of the Great Lakes reported snow amounts of near record proportions (Charts IV and V). These heavy deposits appear to have been mainly a consequence of proximity to the principal storm tracks and overrunning of the cP air by moist Pacific air masses. Extensive snow cover may have contributed to unusual cold in the Northwest. An added orographic effect along the coasts of Washington and Oregon produced very heavy precipitation in that area as a result of the strong westerlies blowing perpendicular to the mountains.

Most of the East experienced some precipitation with amounts generally above normal. The largest totals were reported from the Ohio Valley and in New England. The former fell mainly as heavy snows, while the New England rains were associated mostly with a small but intense storm which occurred November 4–6 and produced minor flooding in an area not yet recuperated from the devastating floods of August and October. This storm has been briefly described by Kangieser [11]. In the Southeast, Gulf moisture produced spotty but generally adequate precipitation.

7. KONA STORMS IN THE HAWAIIAN ISLANDS

It has been previously pointed out that the only negative 700-mb. height anomaly in the whole of the Pacific was the rather sizeable one of 150 ft. to the northwest of the Hawaiian Islands. It should be remarked that the associated trough was well defined on the monthly mean maps for 700 mb. (fig. 3) and 200 mb. (fig. 8). This trough was remarkably persistent and was located in about the same position on each individual 5-day mean map throughout the month of November, and on each seasonal mean map during the past year [2]. This anomaly was associated with Kona rains in the western Islands which were generally heavy and in some instances record breaking. At Kileaua Plantation, for example, on the north coast of the Island of Kauai, the total rainfall for November stood at 29.09 inches, a 30-year record. The bulk of this rain, 22 inches of it, fell in a 16-hour period over the weekend of the 12th–13th in a particularly intense Kona storm of the type described by Gulick [12]. The resulting flood damage to plantations and truck farms was estimated at over $100,000. It is of interest to note that the departure from normal pattern in the Pacific (fig. 3) resembles that described by Solot [13] as being ideal for producing heavy rain in Kauai.

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CORRECTION

MONTHLY WEATHER REVIEW, vol. 83, No. 10, p. 222: In legend to figure 9 the last sentence should read, "The N-NE-E wind group *raises* the level of the sea; the SW-W-NW group *lowers* it."

THE RECORD-BREAKING COLD WAVE OF MID-NOVEMBER 1955 IN THE NORTHWEST

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1. INTRODUCTION

A record-breaking cold spell hit Montana on the 11th of November and spread westward and southwestward through the Plateau, persisting in severity for a week, November 11–18, 1955, and causing heavy losses in unharvested crops and produce in unheated storage. At Helena, Mont. the temperature remained below 0° F. for 138 consecutive hours. After this period the cold air pushed into eastern sections causing near-blizzard conditions in the northeastern Plains and Lakes region and producing cold waves as far east as the Appalachians. This very cold air was eventually responsible for the first general snow in the Northeast and the great contrasts in temperature it provided as it lay over New England on the 19th and 20th helped to spawn a most severe storm off New England.

It is frequently the case that when unusually severe cold persists near one coast, the opposite extreme may occur near the other. This is due to the fact that below normal conditions are usually associated with abnormally deep persistent troughs aloft, while above normal conditions are associated with persistent ridges aloft. The distance normally found between long-wave troughs and ridges is such that a trough over the Plateau will accompany a ridge over the East and vice versa. During the period of the situation to be studied the 500-mb. heights in the Northwest were below normal by record amounts, while in the East they were 200 to 400 ft. above normal. Thus while much-below-normal conditions developed in the Northwest in mid-November, temperatures rose into the 80's in the East producing such late-season record high temperatures as 81° F. at Huntington, W. Va., 79° at Cincinnati, Ohio, and 78° at Baltimore, Md. This marked warming in the East, in contrast to the extreme cold in the West, set up ideal conditions for cold waves in the East also, when conditions finally became favorable for the cold air in the Northwest to move eastward en masse.

The cold Arctic air poured initially into Montana on the 11th causing one of the most severe cold spells in history for so early in the season. By the 13th it had produced subzero minima from North Dakota westward through the northern border States to northeastern Washington. Subfreezing minima occurred along the northwest coast and southward into California's Central Valley killing tender vegetables and unharvested grapes.

On the 15th many stations reported record low temperatures for so early in the season, e. g., −29° F. at Helena, Mont., −11° at Spokane, Wash., −3° at Boise, Idaho, and −9° at Ely, Nev. On the same day Portland, Oreg.,

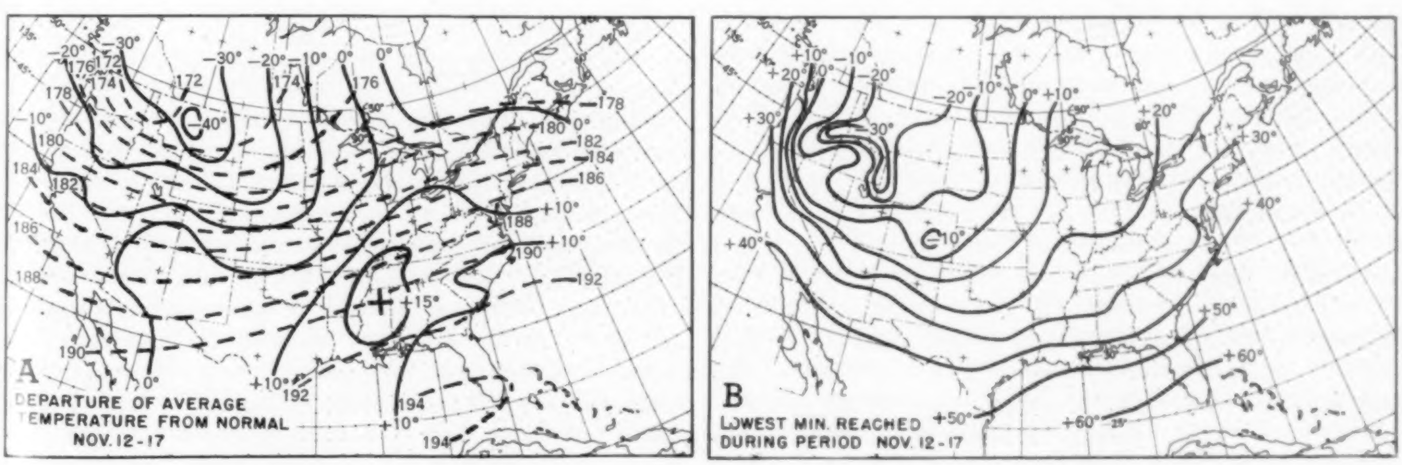

FIGURE 1.—Chart A shows departures of average surface temperatures from normal, November 12–17, 1955 inclusive (solid lines) and mean 500-mb. height contours (dashed lines) labeled in hundreds of feet. Chart B gives lowest temperature minima reached during same period.

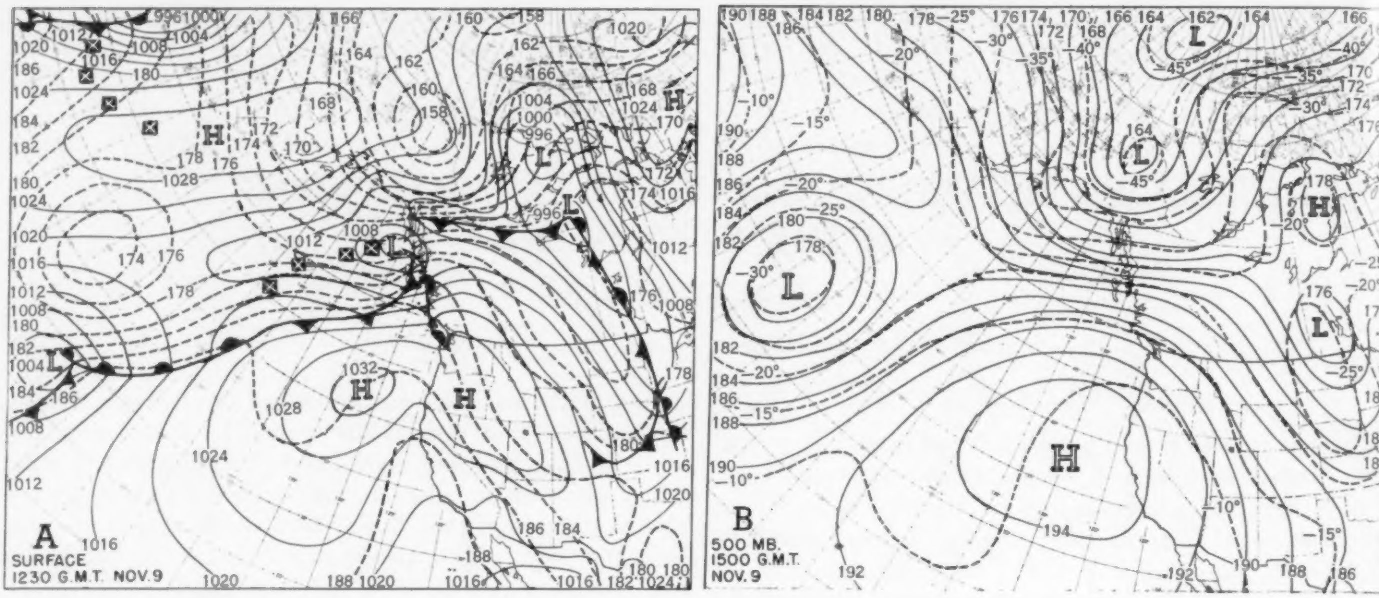

FIGURE 2.—(A) Surface chart and (B) 500-mb. chart on November 9, 1955. On surface chart 1,000–500-mb. thicknesses (dashed lines) are labeled in hundreds of feet. Previous 6-hourly positions of centers are indicated by "X". On 500-mb. chart isotherms (dashed) are labeled in °C. and height contours (solid) in hundreds of feet. Flags on wind shafts represent 50 knots, full barbs 10 knots, and half-barbs 5 knots.

reported a record early-season low of 13° as subfreezing minima extended southward along the coast to Eureka, Calif. At Salt Lake City, Utah, a −14° F. low on the 16th was 14° lower than ever before recorded during November. The average temperature on this day was 1°, or 38° below normal, the greatest daily departure ever recorded at Salt Lake City during any month. In Washington it was the longest severe cold spell on record for November, with Astoria having 135 consecutive hours below freezing. Wyoming experienced average temperatures nearly 25° below normal with several stations in the Yellowstone Basin reporting average temperatures near or below zero. Farther east Nebraska had the coldest mid-November weather since 1940. St. Joseph, Mo. had the coldest November on record with 10° F. on the 16th a new daily record. Figure 1A gives the departures of average surface temperatures from normal during the period November 12–17 with the mean 500-mb. flow superimposed. The 40° below normal in Montana for the period strongly contrasts with the 17° above normal in the Southeast. Figure 1B gives the lowest minima reported by each station during this period.

The protracted nature of this cold spell makes it convenient to divide the period into three parts. The initial phase embraces the first surge of cold air into the Northwest on the 11th and 12th, the middle phase covers the period during which the cold Low aloft performed a loop and came back to its starting point over northeastern Washington, and the final phase starts with the 15th as the upper Low and the associated cold dome moved out of the Northwest.

It will be seen that this cold spell was not characterized by abnormal surface anticyclonic conditions but rather was due to the persistence of an abnormally cold Low at upper levels. The thickness of the air column directly under the upper low center between 1,000- and 500-mb. pressure levels was generally 1,400 to 1,600 ft. thinner (21° to 24° C. colder) than normal for almost a week. Such a deep layer of cold air had an important bearing on the extreme surface temperature anomalies observed, since the thickness of an isobaric layer is directly proportional to the mean temperature in the vertical.

It is our purpose to study and record some of the synoptic aspects of the situation which produced such a record-breaking cold spell both as to intensity and duration at such an early date. It is also planned to examine some details of the vertical structure of the cold dome.

2. ANTECEDENT CONDITIONS AND PROGNOSTIC INDICATIONS

Figure 2A shows the conditions at the surface at 1230 GMT, and figure 2B shows the 500-mb. picture at 1500 GMT on Wednesday, November 9, about 36 hours prior to the first penetration of cold air at the surface into Montana. At this time there was a cold core of somewhat less than 15,800 ft. (fig. 2A) in the 1,000–500 mb. thickness field over Alaska. This is equivalent to a mean temperature of −36° C. in the column of air below the 500-mb. Low. A weak wave cyclone was just entering the coast at the surface about 600 miles south of the upper Low, in such a way relative to the upper contours that it was approaching the delta or exit region of an upper confluence pattern.

Accordingly, most forecasters would look for at least some deepening of the surface storm, not only because of the contours aloft, but because the wave cyclone would be approaching an area in the lee of the Continental Divide

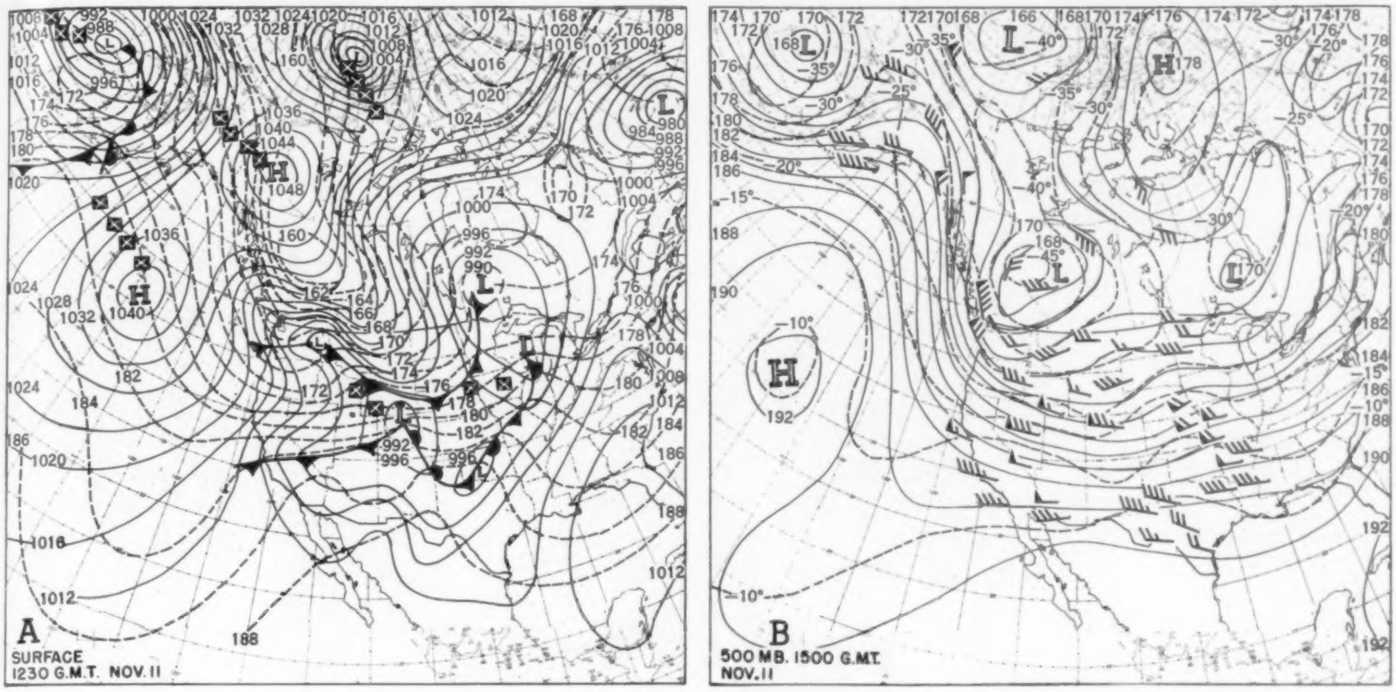

FIGURE 3.—(A) Surface chart and (B) 500-mb. chart on November 11, 1955.

which is normally divergent. However, in order for the wave to deepen enough to produce appreciable cold advection to its rear, while moving parallel to the upper flow, the upper heights would have to fall simultaneously. A southeastward movement of the upper Low and its associated cold core from Alaska would thus tend to result. Therefore, it seems clear that upper heights would have to fall over southwestern Canada if these effects were to be realized. No height falls aloft had been in evidence prior to this time which could be extrapolated toward southwestern Canada. Thus, the signal that the cold Low aloft was about to plunge southeastward into Washington State, Idaho, and Montana, was certainly not clearly in evidence at this time. It should also be pointed out that in terms of large-scale phenomena the clue to the turn of events appears likewise elusive. There had been no sudden or abnormal deepening evident upstream or in fact anywhere over Asia prior to November 9 which could have dispersed eastward at the group velocity.

Computations of movement of the 500-mb. Low using grid methods of averaging the geostrophic flow around the vortex such as the Wilson [1] adaptation of the Riehl-Haggard method, failed to indicate the nature of the ensuing development also. As can be readily guessed by merely looking at the November 9, 500-mb. contour pattern over Alaska and environs in figure 2B, the existing momentum would carry the Low east and northeast.

In fact 24 hours later a filling Low center northeast of Aklavik, N. W. T., did verify the computation well. However the main 24-hour 500-mb. height fall plunged southeastward to British Columbia and increased in magnitude from 600 ft. over Alaska, to 1,000 ft. over British Columbia at 1500 GMT on the 10th. This 24-hour 500-mb. height fall area, in the subsequent 24 hours, again plunged south-southwestward across the initial contour pattern into Oregon to produce the 500-mb. pattern in figure 3B. Although the grid method did verify fairly well in 24 hours, it seemed to be a fortuitous result of residual low pressure in the verifying area, *while the developmental kinetic energy was actually plunging southeastward and southward*, propagating the height falls and the bulk of the cold dome with it. Of course it might be said that the grid method isn't expected to predict this aspect of what occurred since it should only work for barotropic or semibarotropic conditions. Actually most upper Lows are at least similarly baroclinic and even so respond moderately well to the mean flow around the periphery, so long as there are no environmental factors operating to change the peripheral mean flow. Of course, with such environmental factors operating, the longer the effects of the initial conditions are projected forward, the greater will be the error in the final result.

In retrospect however, the following clues, which were available on November 9, seem to take on added importance in explaining some of the changes in the peripheral circulation which produced the tremendous height falls over the northwestern States within 48 hours after the initial conditions pictured in figure 2:

(1) The major ridge at 500 mb. had retrograded in the previous two days from a position inland over eastern Washington. Furthermore, there had been persistent height rises in the Gulf of Alaska for at least 36 hours indicating rather strong anticyclogenesis was taking place.

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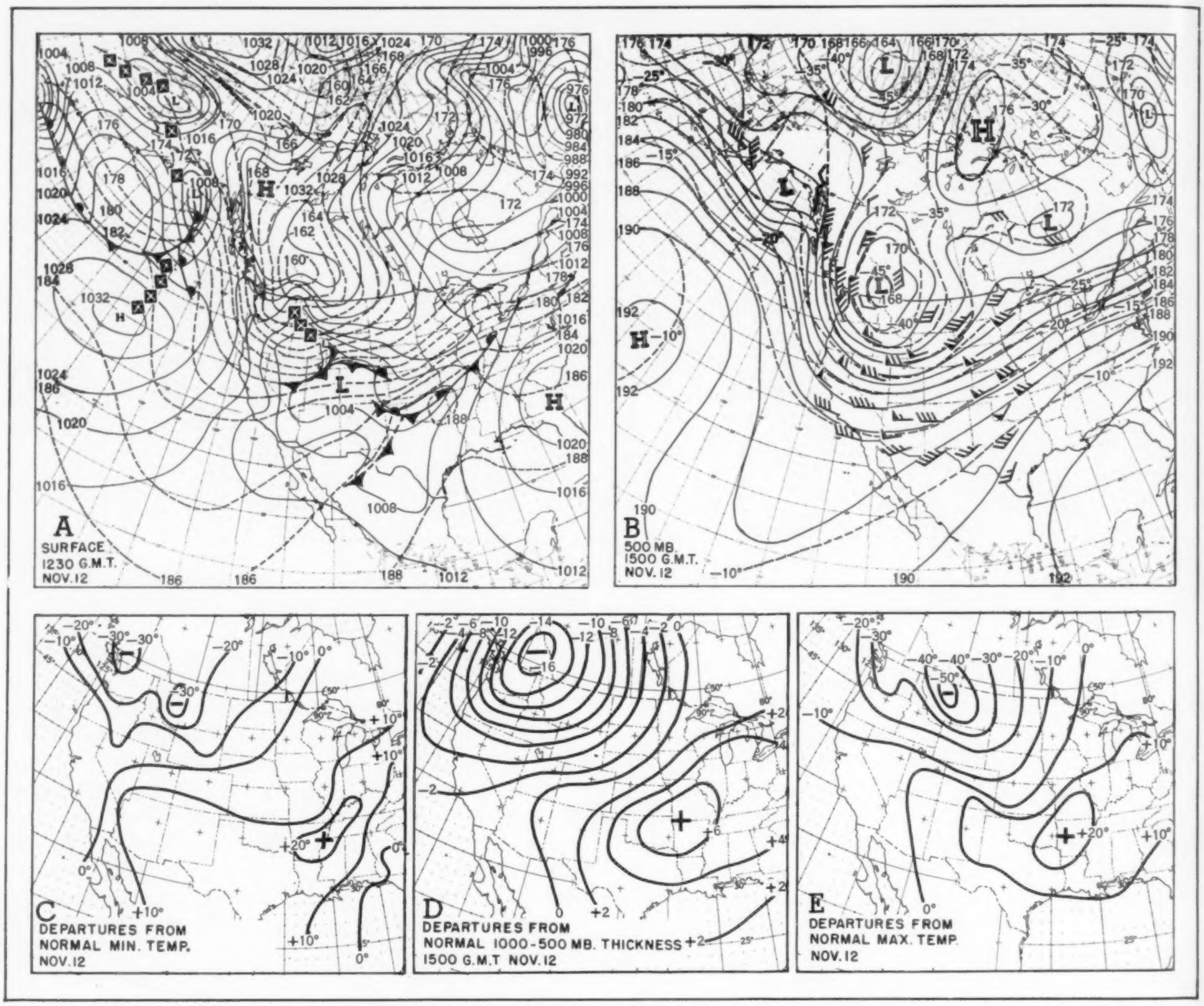

FIGURE 4.—(A) Surface chart and (B) 500-mb. chart on November 12, 1955. Chart (C) shows departures from normal of surface minimum temperatures in °F., and chart (D) shows departures from normal of 1,000–500-mb. thicknesses labeled in hundreds of feet, (E) departure from normal of maximum temperatures.

(2) Cold advection at 500 mb. was indicated toward southeast Alaska, tending to lower heights over southwestern Canada.

(3) Warm advection over the Bering Sea pointed to further height rises over western Alaska, which would serve to keep the gradient strong on the west side of the upper vortex. This would favor propagating the momentum of the northerly flow southeastward, as the gradient to the southeast weakened due to falling heights in that area.

(4) The fourth factor was the strong confluence zone at 500 mb. straddling the coast near 55° N. The entrance zone off the coast may be interpreted as an area of accumulation of air and the exit zone over southwestern Canada as one of depletion. This would tend to produce height rises and anticyclogenesis at the entrance and height falls near the exit of the confluence zone causing further retrogression of the ridge off the west coast allowing the Alaskan Low to plunge southeastward.

In addition to the failure of the grid method of computation, it should be pointed out that other auxiliary tools normally available for prognosis also did not indicate what was to transpire. One such tool, the advection of vorticity by the 500-mb. Fjørtoft [2] space mean flow (not shown) not only did not indicate what was to transpire, but in fact indicated that the vorticity would move to the northeast from Alaska. This is a common failing of the Fjørtoft method. It cannot forecast this important mechanism of plunging since this very process radically alters the space mean flow.

The hemispheric numerical barotropic prognostic similarly did not predict the penetration of the cold upper Low

into the State of Washington. However no developmental virtues have been claimed for the barotropic prognosis. Neither did the baroclinic numerical prognostic predict this event but this is of course not surprising since the vorticity responsible for the development originated beyond the northwest boundary of the data network. The program employed assumes that the vorticity advection is zero at the boundaries. It may well be that the baroclinic prognostic would have predicted this event if the data network included the Alaskan area, but this has yet to be shown. Extended forecasting methods of predicting readjustments in large scale features also fell short of predicting the onset of this cold spell in the extreme Northwest, indicating indefinite or conflicting evidence in the large-scale features. It was not until 1500 GMT on the 10th that indications were sufficiently definite for this severe condition to be included in the NWAC 500-mb. prognosis for 0300 GMT, November 12.

Since the Gulf of Alaska region and the Yukon are favored sites for the generation of dynamic instability [3] with enormous effects on the weather over the United States within 48 hours, much more study must be made on this problem, and particularly in this area.

3. INITIAL PHASE OF THE COLD WAVE

By 1830 GMT on November 10 (not shown), an Arctic cold front at the surface was crossing the Canadian border and about to invade Montana, having moved southward in the rear of a deep (982 mb.) surface Low in Manitoba. This deepening had resulted from the weak surface wave cyclone which had crossed the coast of southeast Alaska on the 9th directly beneath the strong upper height falls plunging southeastward. By 1230 GMT on the 11th (fig. 3A) the surface Arctic air was well entrenched in the northwestern Plains while the 1500 GMT 500-mb. Low was centered over British Columbia (fig. 3B) with Prince George, B. C., reporting −45° C., indicating an abnormally cold upper vortex indeed. By this time 500-mb. heights had fallen in 48 hours almost 2,000 ft. at Seattle, Wash., while 1,000–500-mb. thicknesses were more than 1,400 ft. (21° C.) colder than normal in the vicinity of the upper vortex. This resulted in surface maximum temperatures in Montana on the 11th being 40°–50° F. lower than the previous day, with maxima in the north central areas not going above 10° F. At 500 mb. on the 11th (fig. 3B) the gradient over the northwestern States was very weak with average winds of about 30 knots, while the northerly current west of the Low was relatively strong, averaging 75 knots or possibly more.

By 1500 GMT, November 12 (fig. 4B) the upper Low had been propagated southward to the weak gradient area just north of Spokane, Wash., by the strong northerly jet along the coast of southeast Alaska and British Columbia. The 500-mb. temperature lowered to −43° C. at Spokane and 1,000–500-mb. thickness departures from normal increased 400–800 ft. from the previous day producing a departure of 1,600 ft. (24° C.) in the lower half of the atmosphere near northeastern Washington and northern Idaho.

This caused a further lowering of surface maximum temperatures over the northwestern States on the 12th. From the previous day's values of 10° to 20° F., maxima dropped to 0° to −10° F. in eastern Montana and into the 20's along the coast of Washington.

Figure 4C shows the departures from normal of minimum temperatures and figure 4E shows the departures of maximum temperatures in comparison with the 1,000–500-mb. thickness departures on the 12th (fig. 4D). The minima were 30° F. or more below normal while the maxima were 50° F. or more below normal at some areas in the Northwest. By the morning of November 13, minima ranged from 30° below zero at Cutbank, Mont., to near zero from the Dakotas westward through Wyoming and northern Nevada, except for the coastal regions. Seattle had a minimum of 13° F., the second morning the minimum dropped below 15°.

4. MIDDLE PHASE OF THE COLD SPELL

The contours around the Low near Spokane, Wash., at 500 mb. on November 12 (fig. 4B) exhibit considerable eccentricity (80-knot winds west of the center and 30 knots east of the center) suggesting that the maximum cyclonic vorticity would propagate toward the weaker gradient area to its east. This actually occurred but only in the form of a short-wave trough moving east-northeastward toward James Bay (southern Hudson Bay). At the same time a weak-appearing short-wave

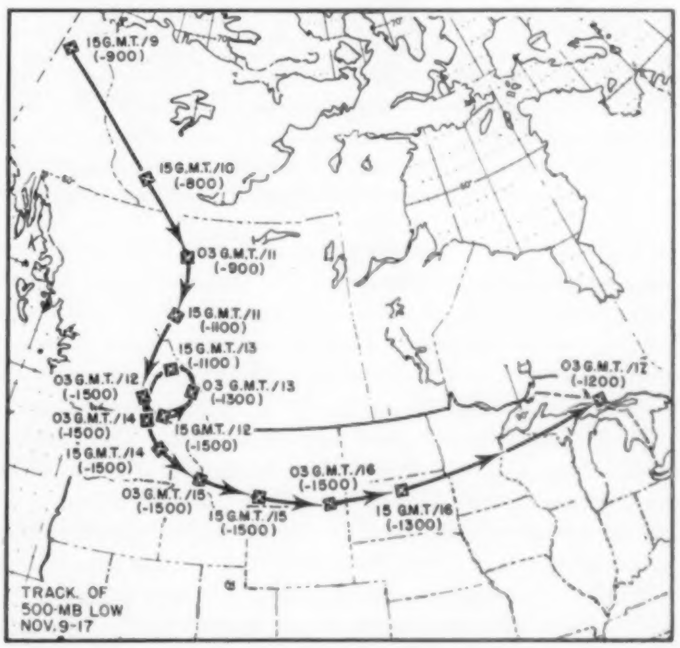

FIGURE 5.—Track of 500-mb. Low during period November 9–17. Date and time groups are separated by slants with departures from normal of central height values (feet) enclosed in parentheses. Successive positions of center at 12-hour intervals are indicated by "X".

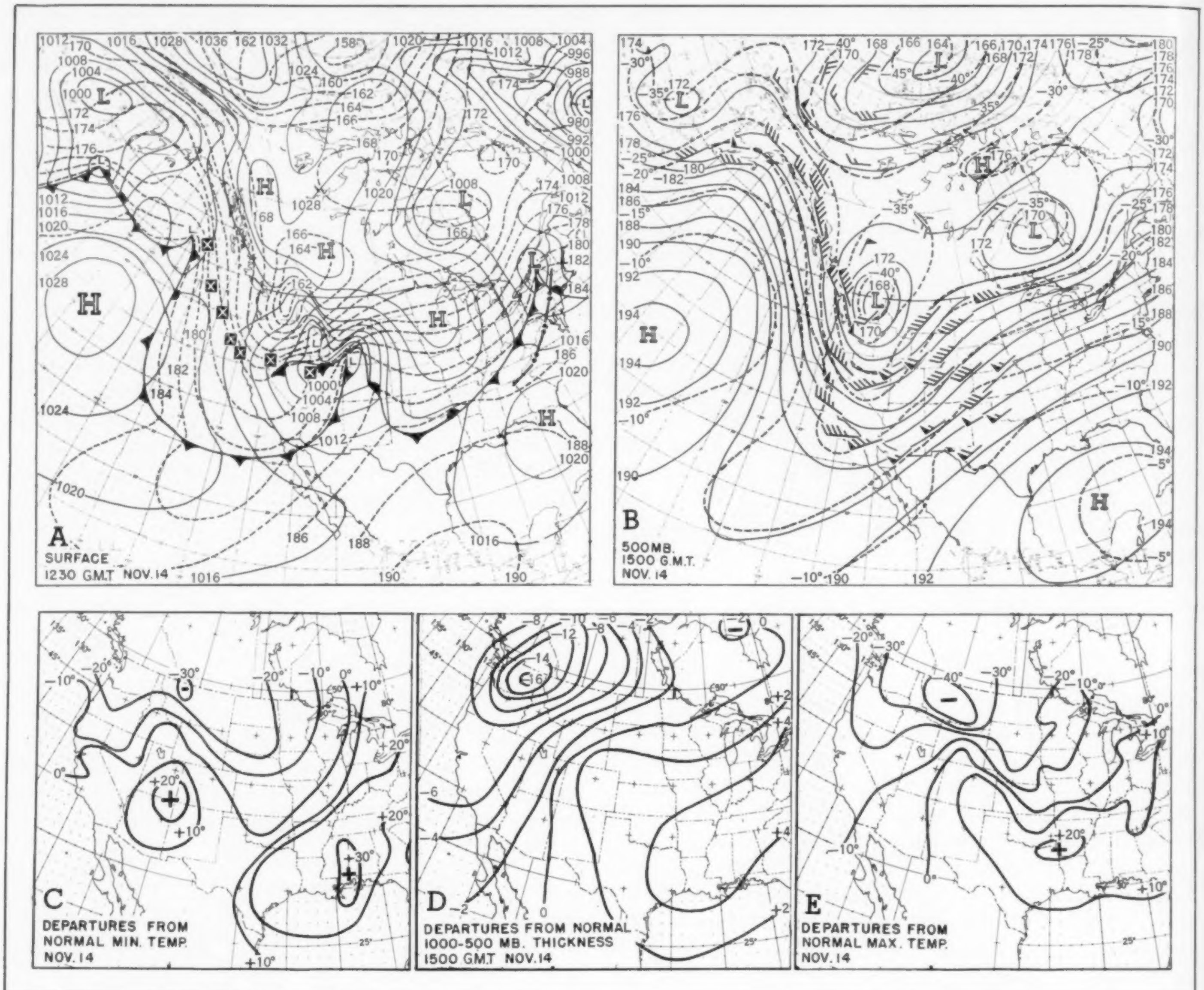

FIGURE 6.—November 14, 1955. (A) Surface chart, (B) 500-mb. chart, (C) departure from normal of surface minimum temperatures, (D) 1,000–500-mb. thickness departure from normal, (E) departure from normal of surface maximum temperatures.

undulation of the contours was rounding the long-wave ridge in the strong westerly current in the Gulf of Alaska, having resulted from a 24-hour height fall of 600 ft. in the ridge over this area. This perturbation was associated with a weak "A" (CIT) type Low [4] at the surface in the Gulf of Alaska (fig. 4A).

In the absence of such an approaching short wave, height rises probably would have occurred in the stronger gradient area to the west of the 500-mb. Low near Spokane, and the whole vortex would have moved eastward ending the cold spell in the Northwest. However the rapid southward translation of this minor feature down the east side of the long-wave ridge in the Gulf of Alaska introduced height falls into the west and southwest quadrants of the main upper vortex. The net effect on the main cold core circulation was to produce a small cyclonic trajectory to its center over British Columbia (fig. 5) together with its associated 1,000–500-mb. thickness anomaly, so as to return the cold core to northeastern Washington on the 14th. By this time the surface "A" type Low was in the central Plateau (fig. 6A) and the 1,000–500-mb. thickness departures were again more than 1,600 ft. (24° C.) colder than normal over Washington. The associated departures from normal of the surface maximum and minimum temperatures (fig. 6C and E) were thus very similar to those reported two days earlier. For example, below zero minimum temperatures were registered on the 15th in eastern Washington, Oregon, Idaho, Montana, Wyoming, northern Utah, and Nevada. Seattle had its lowest minimum of 6° F. during this phase of the cold spell. Ukiah, Oreg., a little south of Pendleton, reported a −32° F. minimum.

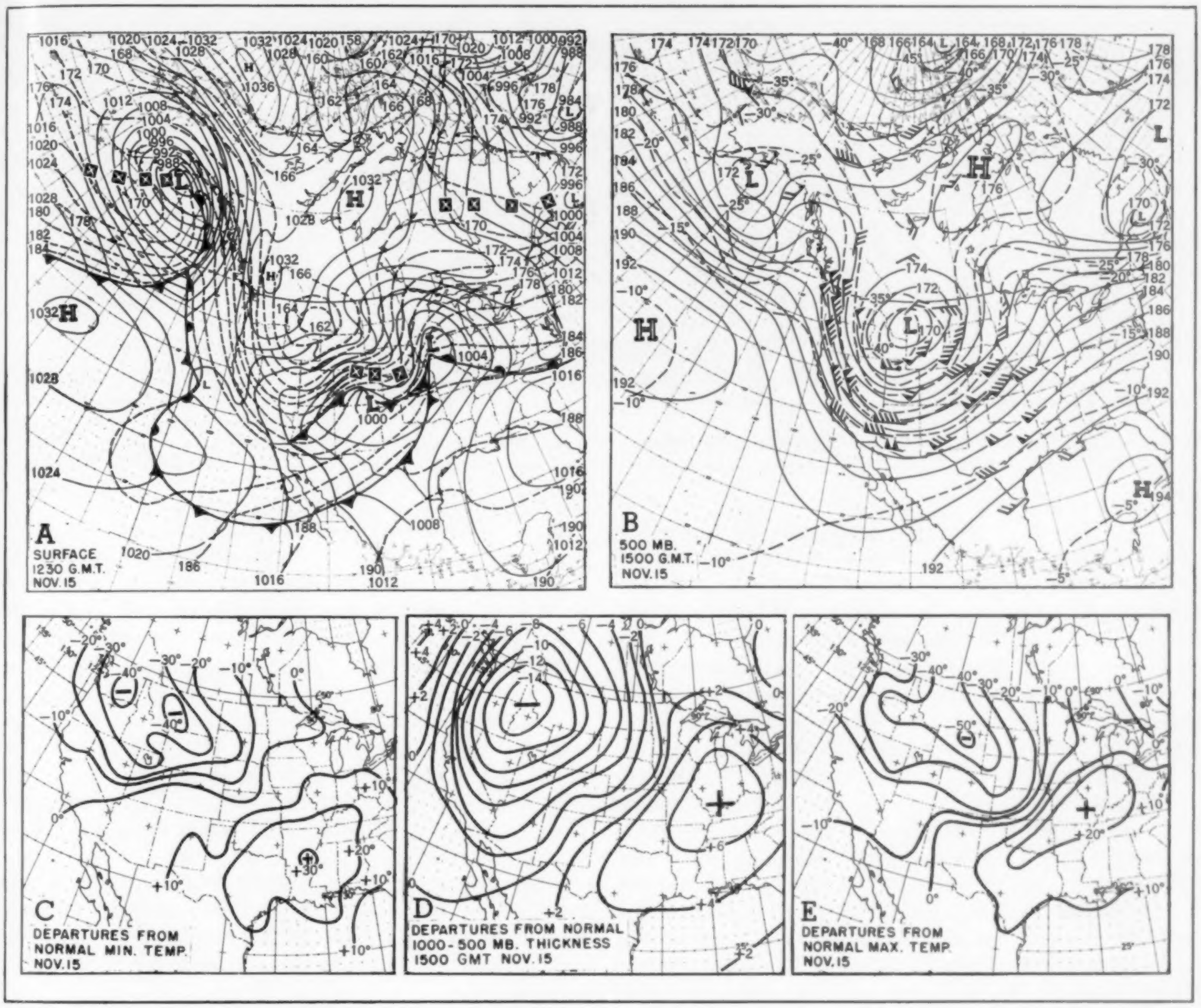

Figure 7.—November 15, 1955. (A) Surface chart, (B) 500-mb. chart, (C) departure from normal of minimum temperatures, (D) 1,000–500-mb. thickness departure from normal, (E) departure from normal of maximum temperatures.

The surface pressure pattern for 1230 GMT, November 14 in figure 6A has long been recognized as the type which precedes cold waves in Utah. In 1931, Hales [5] wrote that for a cold wave to sweep the Utah section of the Rockies, the center of the High must be placed well to the west of the Divide with a vigorous Low emerging from the coast of Oregon or Washington and passing to the southeast through southern Utah.

Such Lows are now generally referred to as "A" type Lows after I. P. Krick and R. D. Elliott who originally developed the CIT weather types [6]. A necessary concomitant of these storms aloft is a deep cold trough over the Plateau near 115° W. and a stationary long-wave ridge near 145° W. The first phase (day) of this type is when the Low breaks off ("skagerraks") in the Gulf of Alaska. In the current situation this was on the 12th. Average timing for this type requires that it be a deep storm near Moosonee, Ont., about 6 days later. The current analogue reached Moosonee on the 17th after passing across the Lakes as a severe storm.

Perhaps the most famous "A" type analogues of recent memory were those of January 1949. The maps of January 7–9, 1949, both surface and 500 mb., were very similar to the current situation from the 9th to the 14th. However there the similarity ends. For subsequent to January 9, 1949, the cold cyclonic core plunged south-southwestward to southern California, stagnating there for a few days and causing snow at sea level in the Los Angeles Basin. In the current situation the cold vortex behaved in a more conventional fashion.

To return to some of the more remarkable details of the November 1955, situation, the surface map in figure 6A

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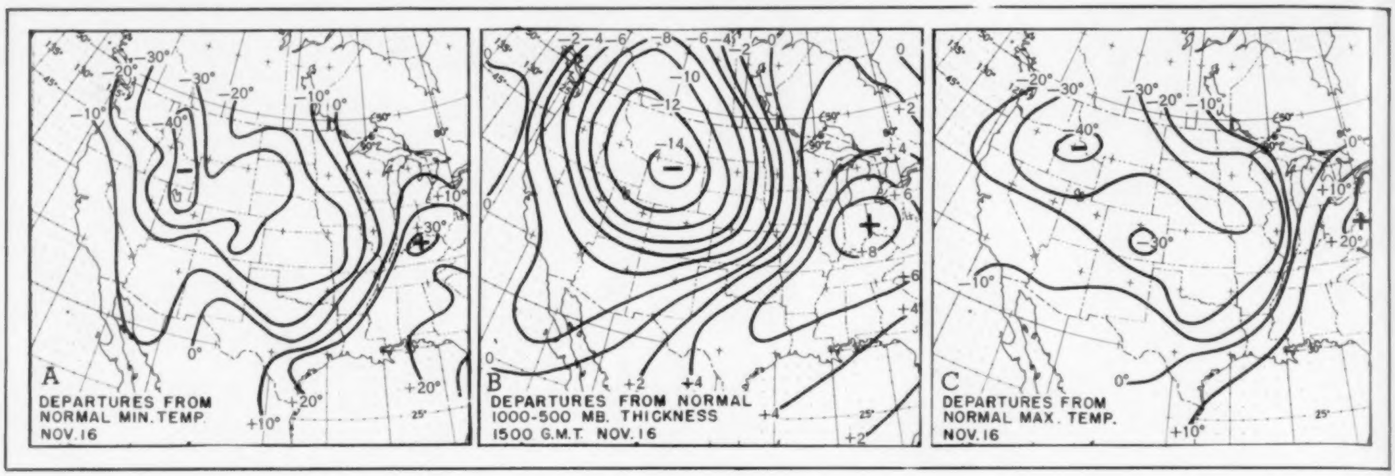

FIGURE 8.—Departures from normal of surface minimum temperatures (° F.) shown in chart (A), departures of 1,000–500-mb. thicknesses (hundreds of feet) in chart (B), and departures of surface maximum temperatures (° F.) in chart (C) for November 16, 1955.

over the Plateau shows the extremely cold core of 16,200 ft. in the thickness lines in eastern Washington, with the strong pressure gradient in the rear of the surface Low over Utah. This gradient intersected almost at right angles the strong gradient of mean temperature lines packed between the Arctic front extending west from the surface Low and the core of the cold air farther north.

Thus cold advection of a strength comparable to the most severe encountered even in mid-winter was indicated threatening Nevada and Utah and points east and southeast. As mentioned before, in the ensuing two days Salt Lake City experienced temperatures lower than ever before so early in the season and the greatest departures of average temperatures from normal ever experienced in its history.

The easternmost wave in the Gulf of Alaska on the surface chart of the 14th was not associated with any upper height falls and therefore proved to be a stable wave and not a new "A" type wave. It therefore had no bearing on ensuing developments.

5. FINAL PHASE OF THE COLD WAVE

During November 14 the cold vortex drifted slowly east-southeastward into southwestern Montana. Figure 7 shows conditions on the morning of November 15. At 500 mb. (fig. 7B) cold advection toward the relatively weak contour gradient was evident in the northern Plains suggesting this was an area of imminent height falls. The speed maximum in the peripheral jet was located in the southwestern quadrant of the upper Low. At the same time a strong westerly stream had developed from 42° to 50° N. along the meridian of ship "P", due to a strong 24-hour height fall of over 1,200 ft. just southeast of Kodiak. This picture clearly suggested large rises propagating into western quadrants of the upper Low in the Northwest in the ensuing 36 hours. Together with indicated height falls east of the Low, the upper Low moved rapidly eastward in response to this isallobaric field. At the surface (fig. 7A) the "A" type Low was well organized as a wave cyclone over Iowa, and the Arctic air at the surface was poised to push rapidly into the Plains. These circumstances contrasted sharply with the warm temperatures existing or expected over the eastern part of the country.

The departure from normal charts for the 15th show that maximum temperatures (fig. 7E) were in excess of 50° F. lower than normal in Wyoming contrasted with over 20° F. above normal from Ohio to Texas. Furthermore minima (fig. 7C) were 30° F. above normal in Arkansas that morning.

Thus on the 16th as the surface cold front moved eastward, severe cold waves occurred as maximum temperatures plunged 40° F. lower in the west central Plains than the previous day while they rose about 30° F. over Illinois and Missouri.

Figure 8 shows temperature and thickness departures from normal on the 16th. Thicknesses (fig. 8B) were more than 800 ft. above normal in Ohio producing maxima (fig. 8C) more than 20° F. above normal in the East, e. g., St. Louis, Mo. reported a maximum of 81° F. Below normal thicknesses of almost 1,500 ft. in Wyoming were associated with 30° to 40° below normal minima (fig. 8A).

The surface storm deepened rapidly as it moved from Iowa to Sault Sainte Marie, Mich., on the 15th and 16th due to strong cyclonic vorticity advection producing large height falls aloft moving rapidly eastward. This resulted in near-blizzard conditions with 2–9 inches of snow from the Dakotas to New England. On the 16th the cold wave edged toward the east coast and maximum temperatures from Missouri to northern Texas fell 40° to 50° below the previous day's values. By this time slow warming was in progress in the Northwest.

6. THE 500-MB. TEMPERATURES

The coldness of the vortex at 500 mb. during this period is very impressive, even though extreme temperatures for

constant pressure surfaces are not yet available in published form. An older publication, "Extreme Temperatures in the Upper Air" [7] containing only very short records, shows that at 5 km. (about 16,400 ft.) the lowest temperature measured up to that time over the whole of North America was −51° C. in January over Alaska. For the continental United States the lowest value was −48° C., again in January, at Bismarck, N. Dak. and Sault Sainte Marie, Mich. The minimum at 5 km. over continental United States for November was −40° C. In the November 1955 situation, −48° C. was the lowest value reported when the Low was in northwestern Canada, while the continental United States stations reported 500-mb. temperatures as given in table 1 (for comparison the 500-mb. values for Nov. 1955 have been converted to 5 km. using a lapse rate of 3° C./1,000 ft. which is the value that prevailed at these levels during the current situation).

Table 1.—*Selected 500-mb. temperatures during cold wave in Northwest, November 1955, compared with previous records as tabulated in [7]*

Station	November 1955					Previous Record		
	500 mb.		Time GMT	Date	Temp. converted to 5 km.	Absolute Nov. min.	Absolute annual min.	Years of record
	Temp.	Height						
	° C.				° C.	° C.	° C.	
Spokane, Wash	−42	16, 870	0300	12	−43	−38	−42	11
	−43	16, 830	1500	12	−44			
	−41	16, 710	1500	14	−42			
	−42	16, 910	0300	15	−43			
Great Falls, Mont	−40	17, 070	1500	12	−42	−36	−44	5
	−40	17, 070	0300	13	−42			
	−38	17, 030	0300	15	−40			
	−42	16, 900	1500	15	−43			
Boise, Idaho	−38	17, 200	1500	12	−40	−32	−36	5
	−38	17, 090	0300	15	−40			
	−39	17, 100	1500	15	−41			
Salt Lake City, Utah	−39	17, 280	1500	15	−42	−35	−36	3
Glasgow, Mont	−41	17, 140	0300	13	−43	−39	−41	2
	−38	16, 970	0300	16	−40			
	−39	17, 040	1500	16	−41			
Lander, Wyo	−38	17, 100	0300	16	−40	Not available		
	−37	17, 180	1500	15	−39			
Rapid City, S. Dak	−41	16, 980	0300	16	−42	−35	−40	2
	−37	16, 950	1500	16	−38			

From table 1 it can be seen that the upper-air temperatures at these stations were substantially lower than previous absolute minima as published in 1947, both for the month of November and even the year as a whole for some stations, particularly Salt Lake City, Utah, and Boise, Idaho.

7. THE STRUCTURE OF THE COLD DOME

In addition to its apparent record coldness throughout the troposphere the upper vortex possessed some other characteristics worthy of note. While perhaps not of record depth, it was nevertheless an unusually deep Low. The 500-mb. height was 1,400 feet lower than normal near the center during much of the period from November 12 to 17.

TROPOPAUSE ASSOCIATED WITH COLD DOME

It also possessed an unusually low tropopause, near or below 24,000 feet throughout most of its history, from Alaska on November 8 through its sojourn in the North-

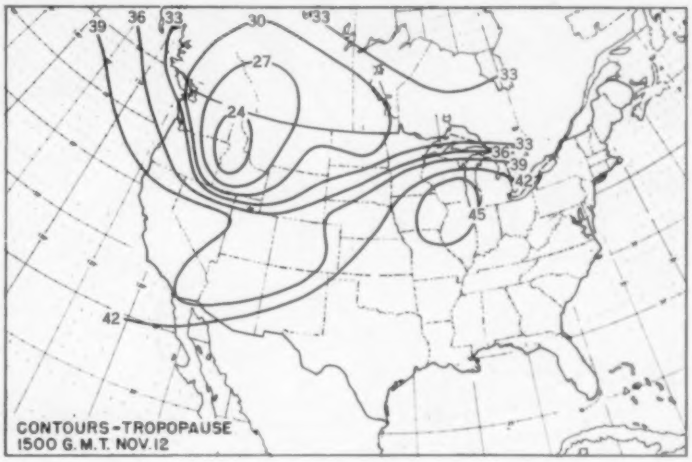

Figure 9.—Contours of tropopause at 1500 GMT, November 12, 1955, labeled in thousands of feet.

west from the 12th to the 16th, retaining this same characteristic eastward to the North Atlantic. Figure 9 shows the tropopause topography at 1500 GMT, November 12. The nadir was somewhat south of the 500-mb. circulation center in figure 4B and seems to have been more closely associated with the vorticity maximum in extreme northeastern Oregon. A similar structure existed two days later at 1500 GMT on the 14th, at which time, as can be seen from figure 5, the Low was completing a loop in its trajectory prior to moving eastward into the Plains. Although drawn as a continuous surface in figure 9, there seems to have been a definite break in the tropopause between Bismarck and St. Cloud as indicated on the cross section in figure 10. The only significant tropopause at Bismarck and stations to the west over the cold dome had a potential temperature averaging about 310° A. This corresponds to the low Arctic tropopauses usually found over cold core Lows.

At St. Cloud there were two definite tropopauses in the sounding with the higher one at about 340° A. being the more significant. The less significant tropopause point was at about 310° A. and was therefore a diffuse continuation of the low Arctic tropopause. The higher point apparently was the same tropopause observed at 150 mb. at Green Bay, Wis., with a potential temperature of 365° A. It might therefore be inferred that the Arctic jet (to be discussed further below) from Salt Lake City to Rapid City at 300 mb. in figure 11 was located between Bismarck and St. Cloud in the region of the tropopause break, even though no wind reports are available between these two stations.

THERMAL PATTERNS AT 300 MB.

As can be seen from the cross-section in figure 10 the tropopause associated with the cold dome in the Northwest was well below the 300-mb. level at some stations. The thermal pattern at 300 mb. in the vicinity of the vortex associated with the tropospheric cold dome is therefore of some interest. This 300-mb. thermal pattern

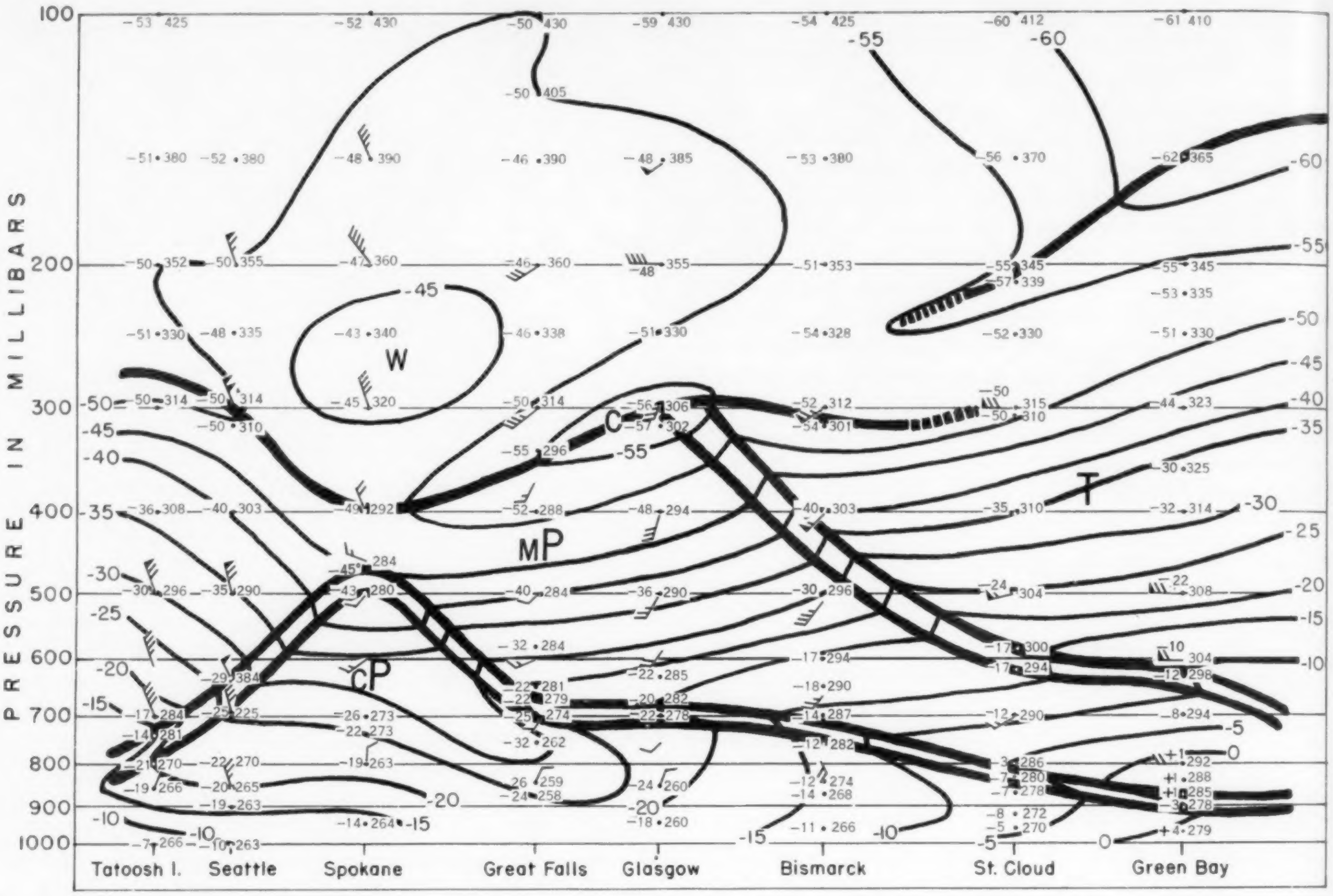

FIGURE 10.—East-west vertical cross-section through cold dome at 1500 GMT, November 12, 1955. Plotting model gives temperature (° C.) to left and potential temperature (° A.) to right. Wind force same as on 500-mb. charts. Double heavy solid lines are frontal zones, single heavy solid lines are tropopauses, and thinner solid lines are isotherms labeled in ° C.

(fig. 11) resembled in many respects the isotherms found by Kochanski [8] associated with stratospheric sinks at 300 mb. in midwinter of 1949. As figure 11 shows, a closed −45° C. isotherm over Idaho delineated the warm core of stratospheric air. This isotherm was practically congruent with the 24,000-foot contour in the tropopause topography. It was almost completely south of the −45°C. cold core at 500 mb. and the tropospheric cold core as represented by the 1,000–500-mb. thicknesses in figure 4A. Actually the warm core at 300 mb. seems to have been most closely associated with the cyclonic vorticity maximum rather than with the center of the vortex. This warm core was surrounded by a colder ring whose axis was along the tropopause intersection with the 300-mb. surface. The colder ring was delineated in the west, north, and east quadrants by the −50° C. isotherm which kinked in the vicinity of the tropopause intersection.

This type of analysis of the 300-mb. isothermal field in the vicinity of dynamic vortices at 300-mb. is standard procedure at the National Analysis Center because it seems to possess a high degree of reality as revealed by cross-sections and is a requisite for three-dimensional consistency.

Increased intensity of the stratospheric sink was evident on later maps when the upper Low was moving eastward through the Great Lakes. On the 17th the 300-mb. charts showed a warm core with an astounding −35° C. isotherm about 300 miles in diameter. Maniwaki, Que., reported −34° C., Buffalo, N. Y., −35° C., while winds of 200 knots in the associated jet axis were reported in close proximity to the south on the equatorward side of the cold ring

JET AXES ASSOCIATED WITH THE COLD DOME

The steepest slope in the tropopause topography from the Plains westward to the coast (fig. 9) was immediately to the north of a jet axis at 300 mb. (fig. 11). This jet axis appears to have been close to the 29,200-ft. contour of the 300-mb. surface. This is about 1,000 ft. lower than the jet associated with the polar front is normally found. It is now pretty well accepted that the location of the polar front jet axis is nearly vertically above the 18,400-ft. contour and the −18° to −20° C. isotherm at 500 mb. Assuming a temperature anywhere between −40° C. and −45° C. at 300 mb., any combination of these 500- and 300-mb. temperatures gives a 300-mb.

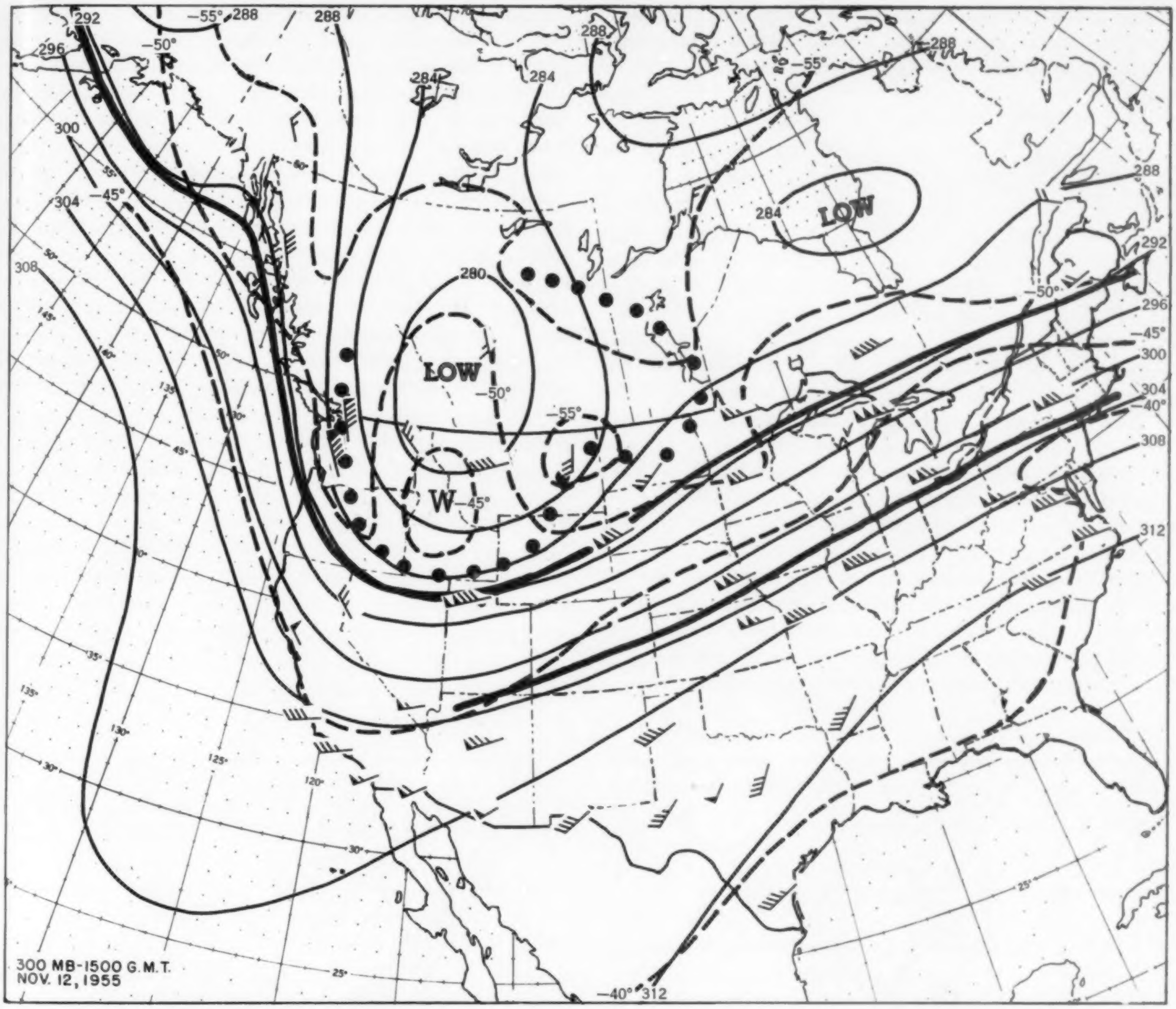

FIGURE 11.—300-mb. analysis above cold dome at 1500 GMT, November 12, 1955. Height contours (thin solid lines) are labeled in hundreds of feet. Isotherms (dashed) are labeled in ° C. Jet axes are heavy solid lines and tropopause intersection is dotted.

contour value of over 30,000 ft. directly above the 18,400-ft. contour at 500 mb. Experience with actual 300-mb. data suggests that the normal height for the polar front jet axis at 300 mb. may be near 30,300 ft. Over the southern Plateau in the current instance, neither the wind data nor the contour gradients suggested a well defined jet axis along the 30,300 ft. contour. This would tend to imply that the horizontal temperature field associated with the polar front was rather weak.

A glance at the thickness lines in Figure 4A shows comparatively little thermal shear in the vicinity of the 18,400–18,600-ft. thickness zone, this being one criterion of frontal intensity at the Analysis Center. By the same token the much stronger horizontal concentration of thicknesses between Salt Lake City, Utah, and Boise, Idaho associated with the Arctic front at the surface seems to have resulted in the secondary jet over the Plateau being the dominant one. This jet continued eastward along the 29,200-ft. contour (fig. 11) and apparently was associated with the main break in the tropopause between Bismarck, N. Dak., and St. Cloud, Minn., as discussed above

Although the polar front jet was weak and diffuse over the Plateau it apparently existed near the 30,300 ft. contour in greater intensity over the eastern sections of the United States due to the stronger baroclinic condition evidence in the 1,000–500-mb. thickness pattern. It also appears to have been well south of the tropopause break. As can be seen from the cross-section, figure 10, however, the polar front at 500 mb. was vertically below the tropopause break. The large horizontal separation between the 500-mb. polar front and its jet axis so much

farther south over the Plains States is somewhat puzzling, but nevertheless seems to be a fact. It may have been due to an abnormal flatness of the frontal slope at upper levels.

FRONTS ASSOCIATED WITH THE COLD DOME

As discussed above in relation to the jet axes at 300 mb., the dominant baroclinic zone over the Plateau was north of Salt Lake City. The southern edge of this zone was near the 17,600–17,800-ft. thickness lines (fig. 4A). This southern edge is generally referred to as the Arctic front, i. e., the separation between cP and mP air. Figure 10 shows its vertical structure in east-west cross-section. It was characterized by a potential temperature of 282–284° A. This is in line with the value of about 286° A. suggested previously [9]. The cP dome reached a height of about 20,000 feet directly below the nadir of the warm Arctic tropopause, and was relatively shallow elsewhere. Figure 12 shows that this front was the most prominent feature of the air column at Great Falls, Mont., at 680 mb. and was also a significant feature at St. Cloud at 810 mb.

Another break showed up in the soundings in the vicinity of an even lower potential temperature of about 270° A., for example at 710 mb. at Great Falls and 910 mb. at St. Cloud. It also appeared in all soundings in the vicinity of the cold dome and is thought to represent the top of a much shallower stratum of real Arctic air, and was associated with representative surface temperatures below freezing. This discontinuity is rarely carried as a separate front in surface analyses since it represents merely a further intensification of the baroclinic temperature field associated with the secondary or Arctic front, and because it is of such limited vertical extent.

Above the cP dome as delineated by the Arctic front was a deep layer of mP air. Ordinarily, away from the proximity to a cold upper vortex the polar front is the vertical termination of the mP air. In the current instance however, at Great Falls, Mont., Edmonton, Alta., Spokane, Wash., and Boise, Idaho, the polar front was indistinguishable from the low Arctic tropopause; for example, in the Great Falls sounding at 350 mb.

The polar front is easily located on most soundings as a stable stratum whose top is at a potential temperature of about 298–302° A. or more, which is about the minimum potential temperature of tropical air in its source region. The east-west cross-section in figure 10 shows the polar front very prominently at Bismarck, St. Cloud, and Green Bay, Wis., at about 300° A. with the strongest vertical wind shear through this frontal zone. Above this frontal surface was a deep stratum of tropical air. From Glasgow west of Spokane there was no tropical air below the tropopause. As is evident in figure 12, the top of the mP

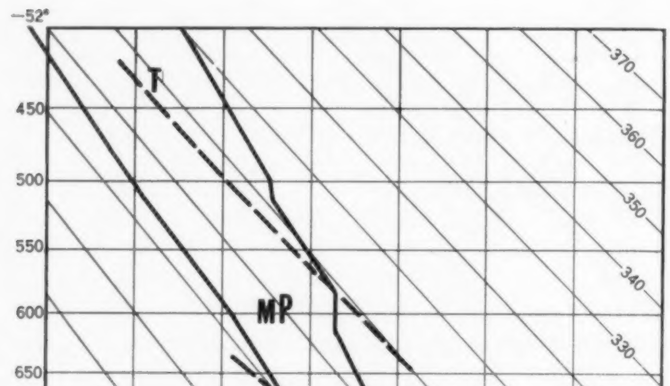

FIGURE 12.—Upper-air soundings for Great Falls, Mont., and St. Cloud, Minn., for 1500 GMT, November 12, 1955. Dashed lines indicate tops of frontal zones; slopes have no significance.

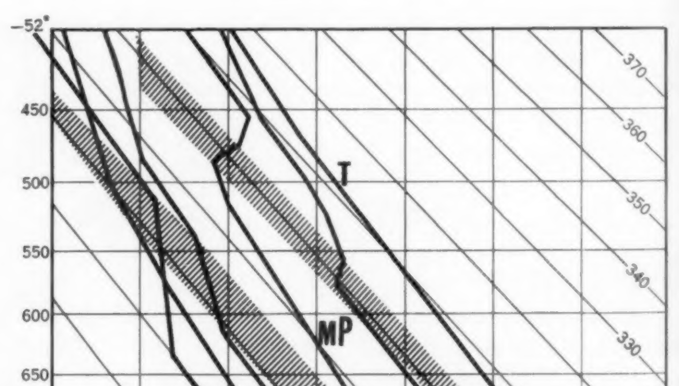

FIGURE 13.—Upper-air soundings on a north-south section through the center of the cold dome, at 1500 GMT, November 12, 1955. Sloping hatched zones connect frontal inversions in adjacent soundings. Slopes have no significance.

air was near 580 mb. at St. Cloud with tropical air above, while at Great Falls tropical air was clearly absent.

Figure 13 shows a series of soundings through the cold dome from Edmonton, Alta, southward to Las Vegas, Nev. The horizontal separation of the soundings on the pseudo-adiabatic chart has no relation to the geographical separation of the stations. The complex structure of the air masses associated with the cold dome is clearly evident. There were four distinct air masses in the vertical. Real Arctic air was at the surface at Edmonton and Spokane topped by an inversion surface at 270° A. This is not carried as a separate front in the surface analysis. Above the real Arctic air was a sloping stratum of cP air topped by an inversion surface evident at Boise, Spokane, and Edmonton with a potential temperature of about 285° A. This is the Arctic front in the surface analysis. Above this was a sloping stratum of mP air topped by an inversion surface at 300° A. Above this stratum was tropical air with potential temperature in excess of 300° A. This stratum was missing at Boise, Spokane, and Edmonton because of the low tropopause.

8. SUMMARY

1. It appears that dynamic instability associated with an unusual confluence in the westerlies normal to the coast of western Canada produced the retrogression which permitted a deep cold upper vortex to plunge southeastward from Alaska to Washington across more than 2,000 feet of height in 48 hours.

2. No current methods of prognosis successfully forecast this event nor even hinted at the readjustment in large-scale features of the circulation which occurred in the 48 hours subsequent to November 9.

3. Record-breaking surface negative temperature anomalies in the northwestern States were produced by the persistence of a dynamic cyclonic vortex over this area.

4. Record-breaking upper-tropospheric low temperatures maintained the deep cyclonic cold dome over this area by virtue of a continued flux of kinetic energy from the developing ridge upstream.

5. The strikingly warm core of stratospheric air at 300 mb. seems to have been most closely associated with the cyclonic vorticity maximum rather than with the center of the vortex, and was well south of the tropospheric cold dome.

6. In the south and east quadrants of the cold dome, tropical air was completely absent from the circulation in the upper troposphere within about 600 miles of the center due to the lowness of the tropopause.

7. A secondary jet associated with the baroclinicity of the Arctic front appeared to be the most prominent aspect of its upper peripheral circulation.

8. Despite the apparent homogenity of its tropospheric wind and thermal circulations, soundings through the cold dome clearly indicated sloping stratification of Arctic, continental polar, and maritime polar air masses within the inner core, with tropical air aloft no closer than about 600 miles.

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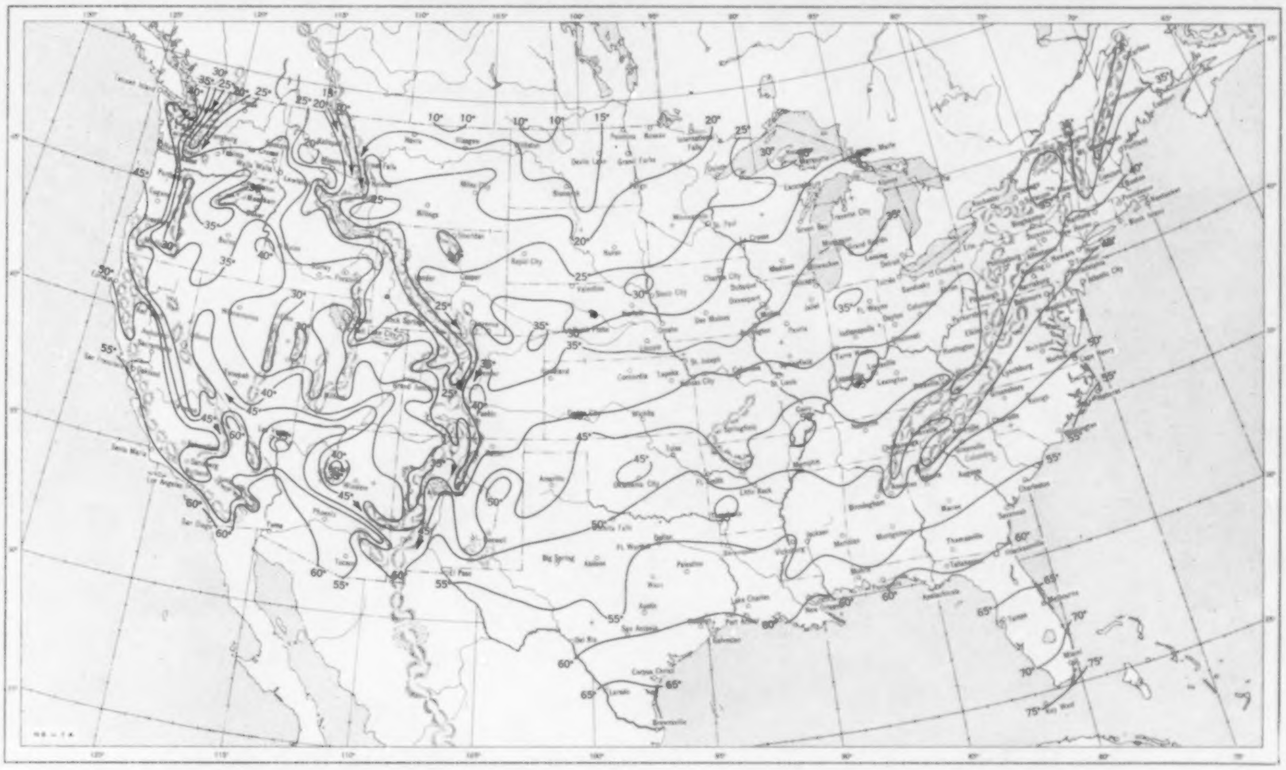
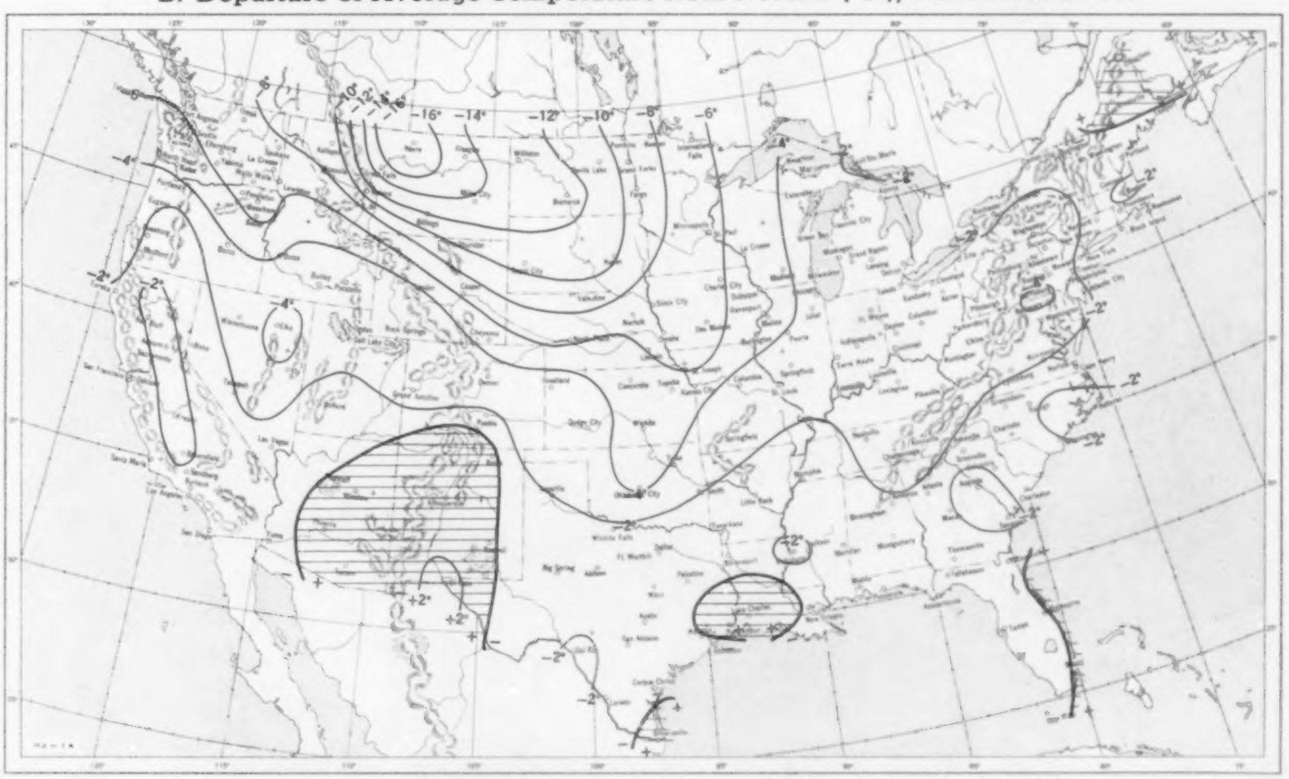
Chart I. A. Average Temperature (°F.) at Surface, November 1955.

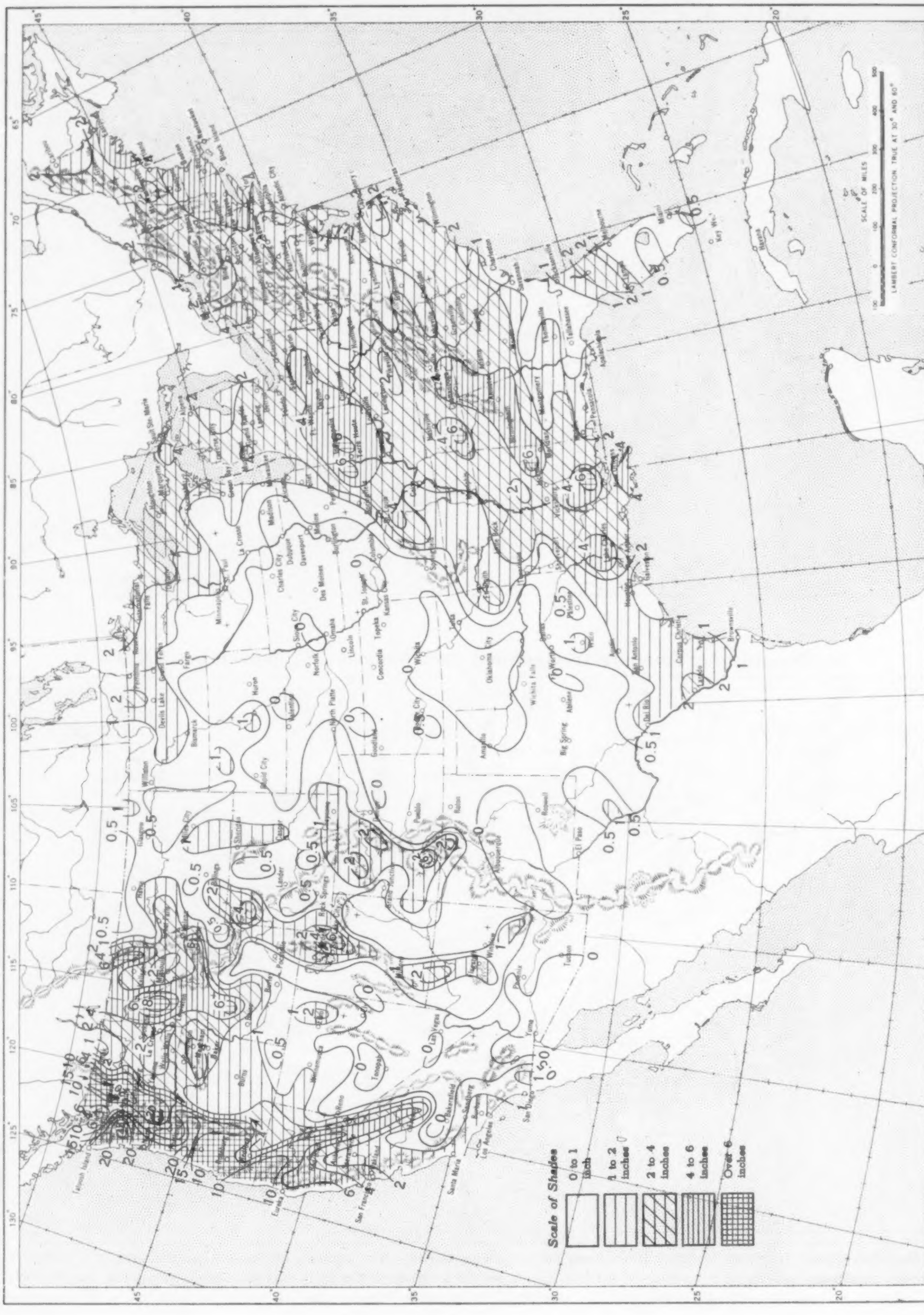


B. Departure of Average Temperature from Normal (°F.), November 1955.



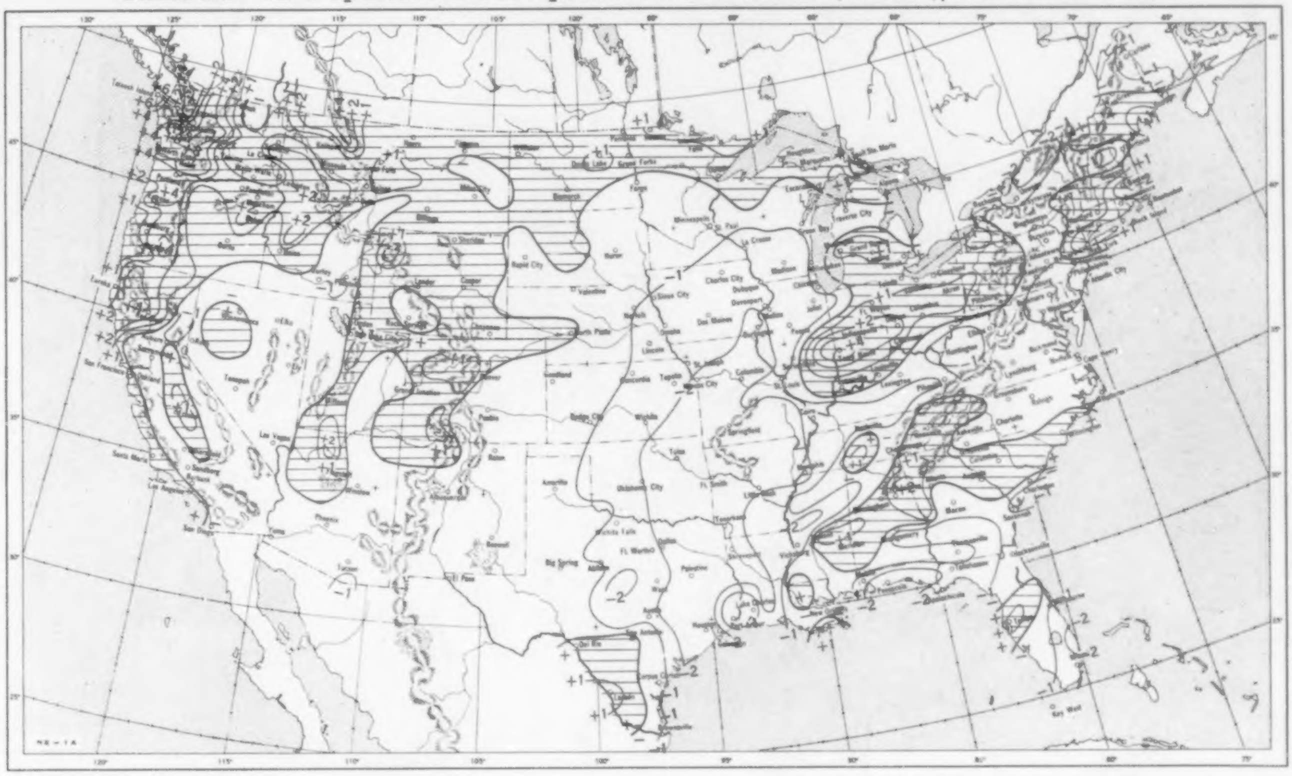
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), November 1955.

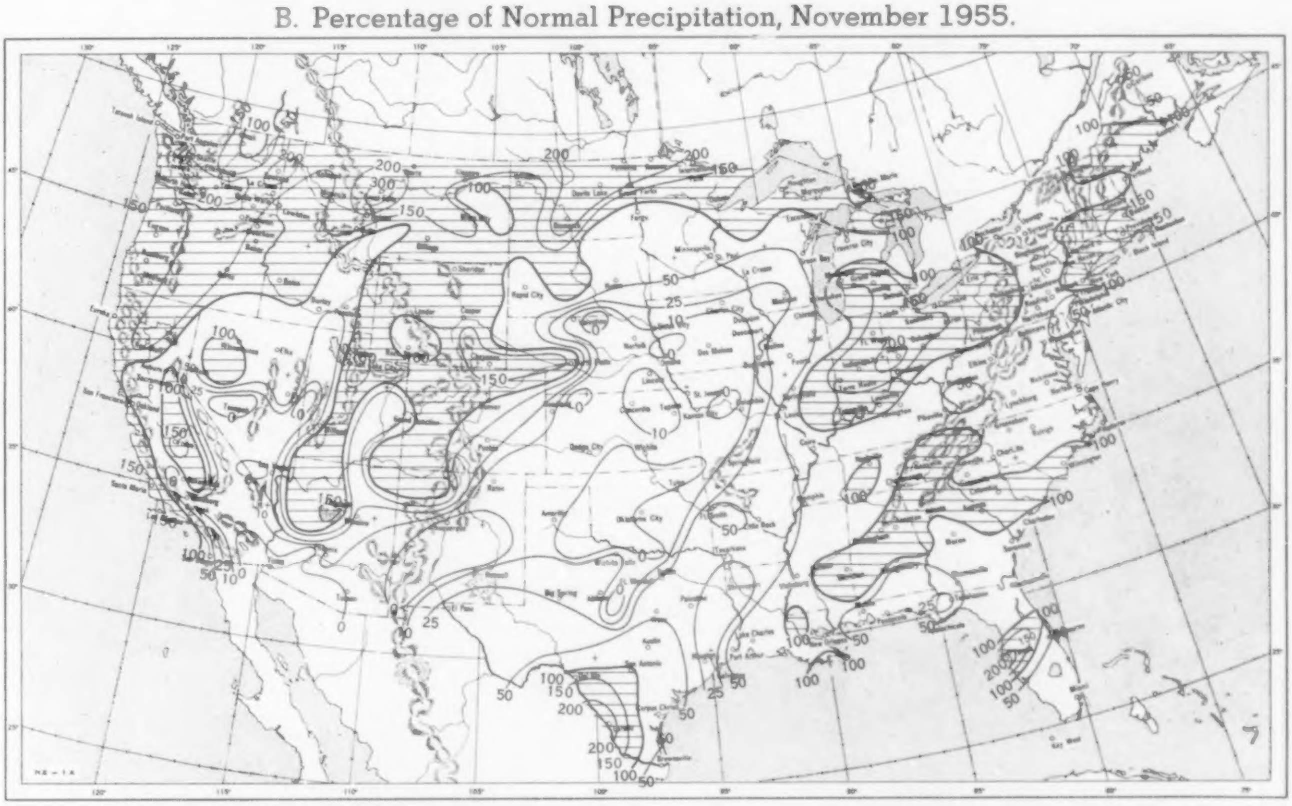


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), November 1955.

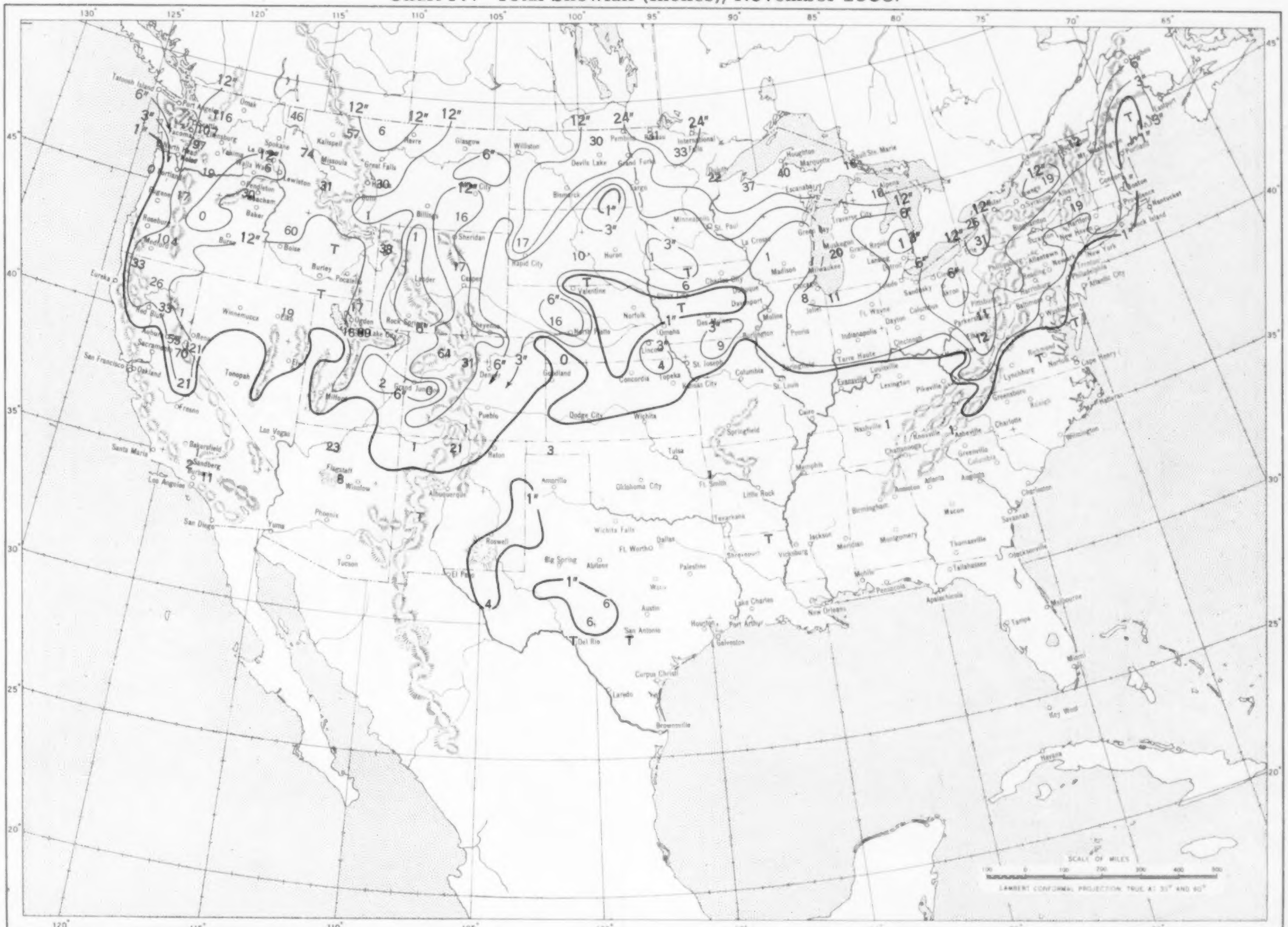


B. Percentage of Normal Precipitation, November 1955.



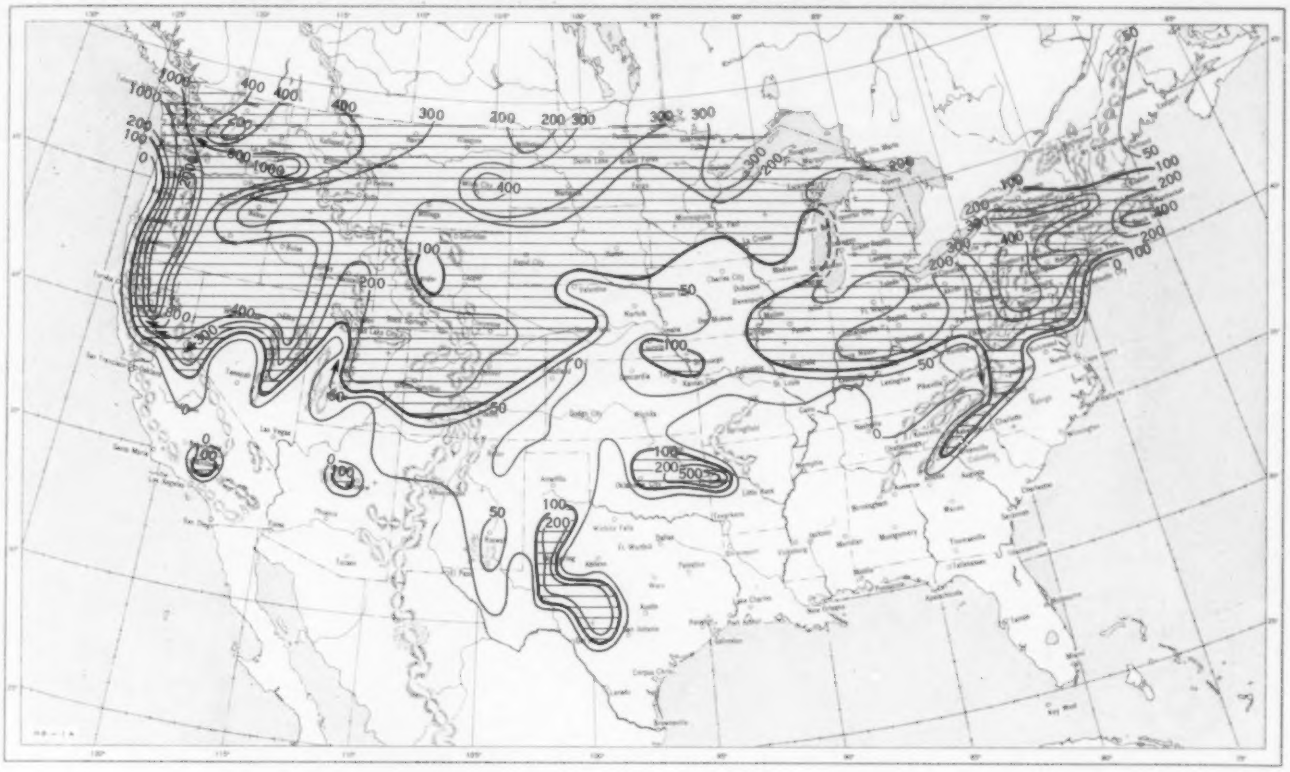
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), November 1955.



This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

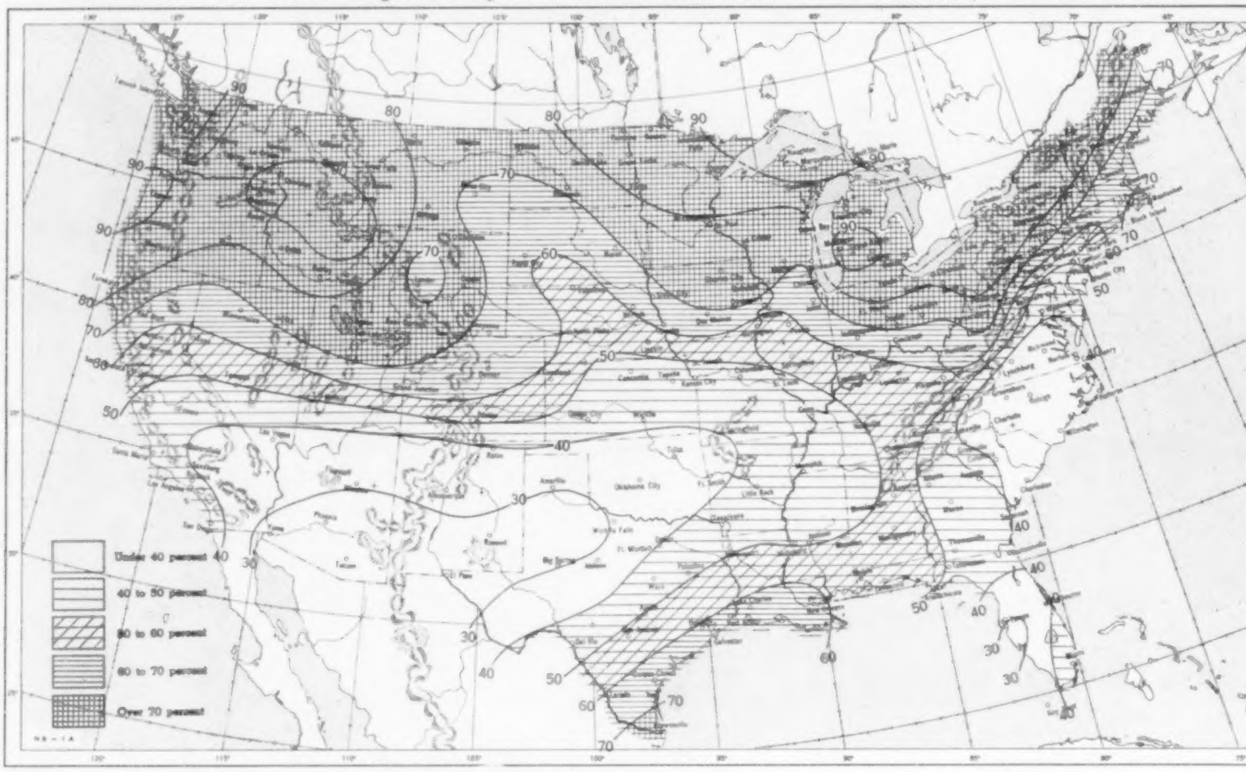
Chart V. A. Percentage of Normal Snowfall, November 1955.



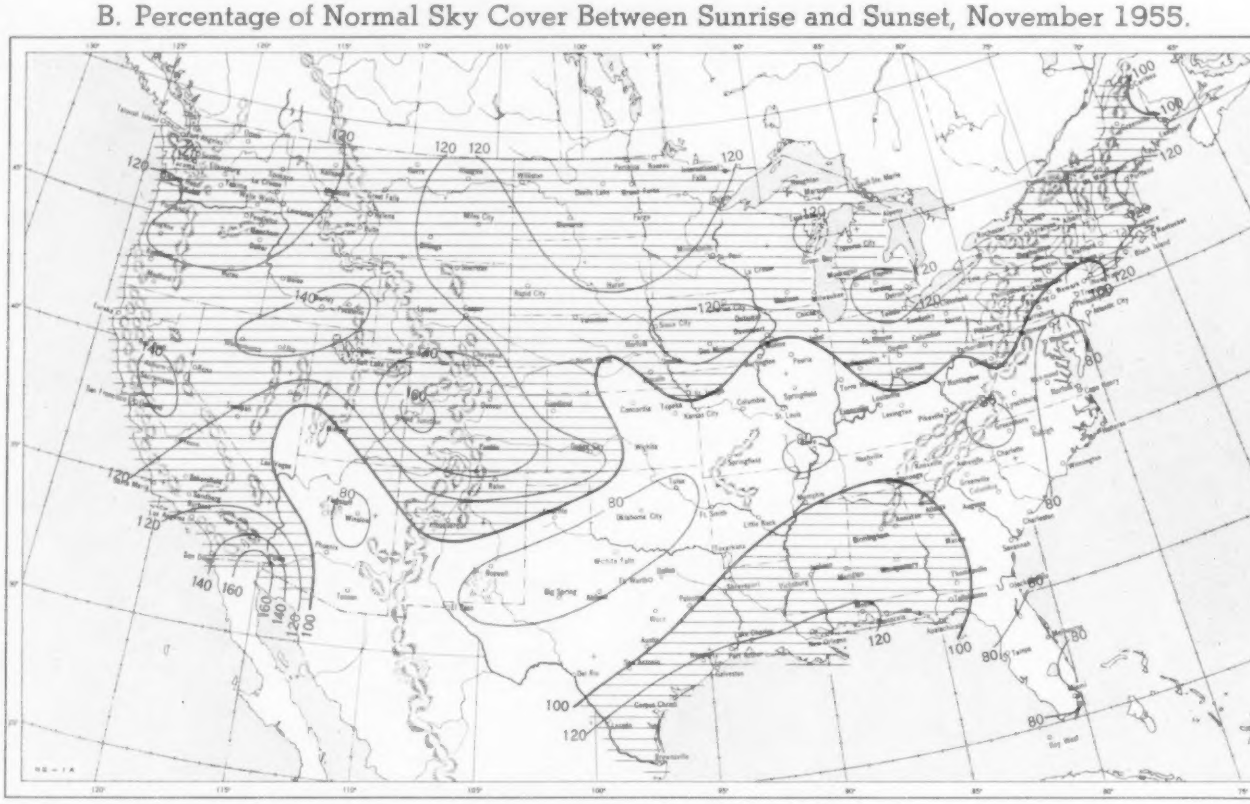
B. Depth of Snow on Ground (Inches).

A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record. B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, November 1955.

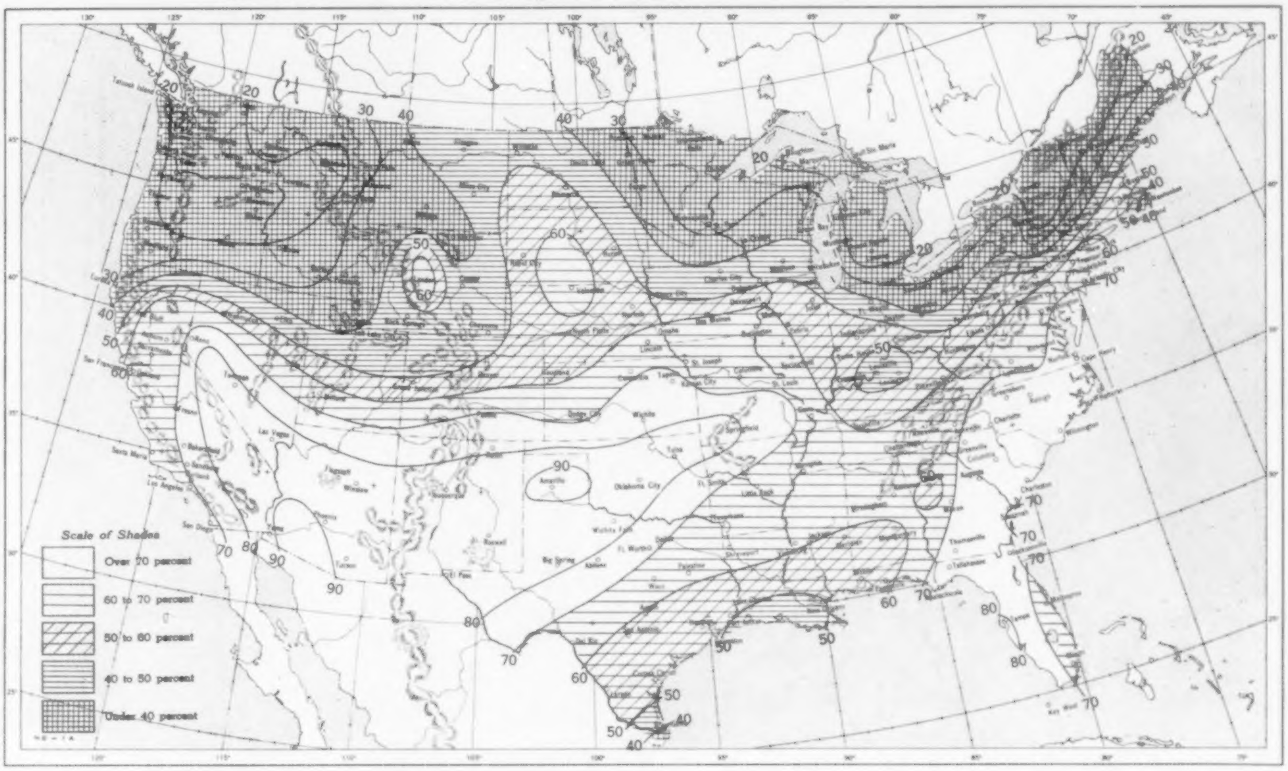


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, November 1955.

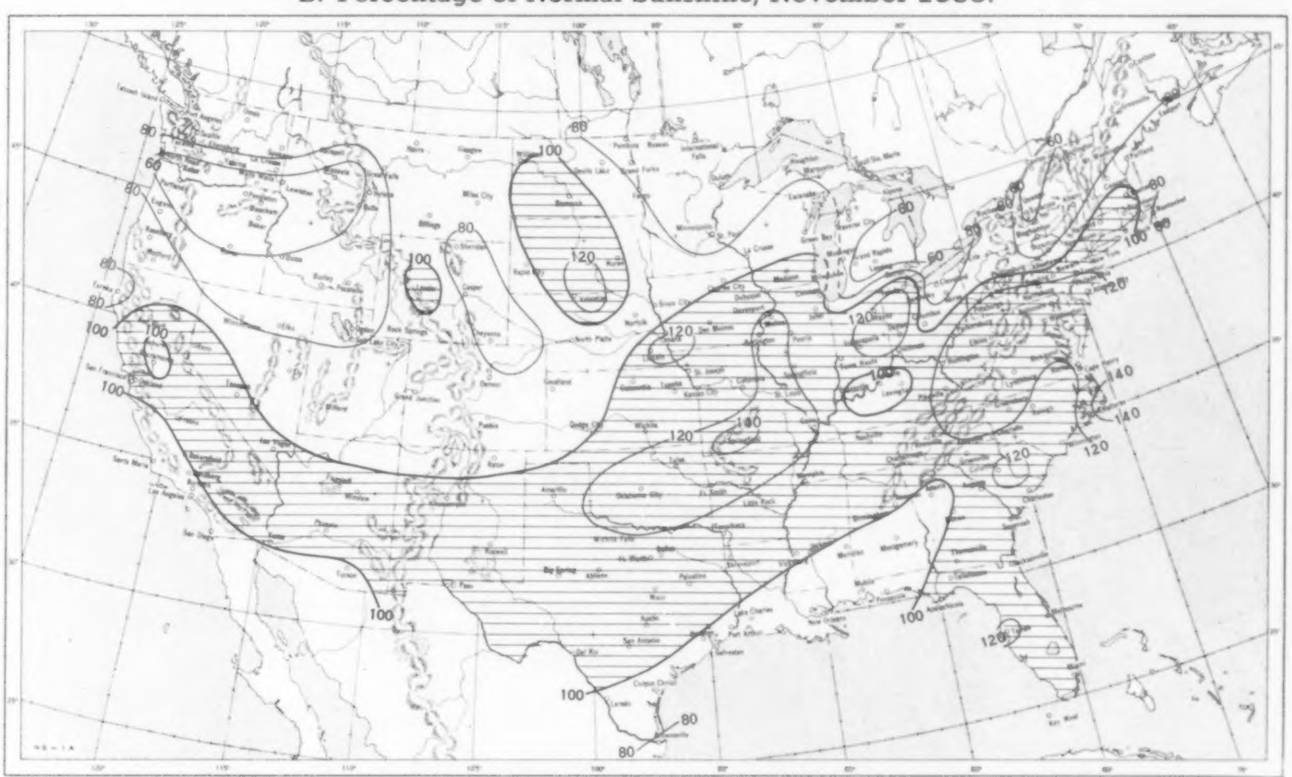


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, November 1955.



B. Percentage of Normal Sunshine, November 1955.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, November 1955. Inset: Percentage of Normal Average Daily Solar Radiation.

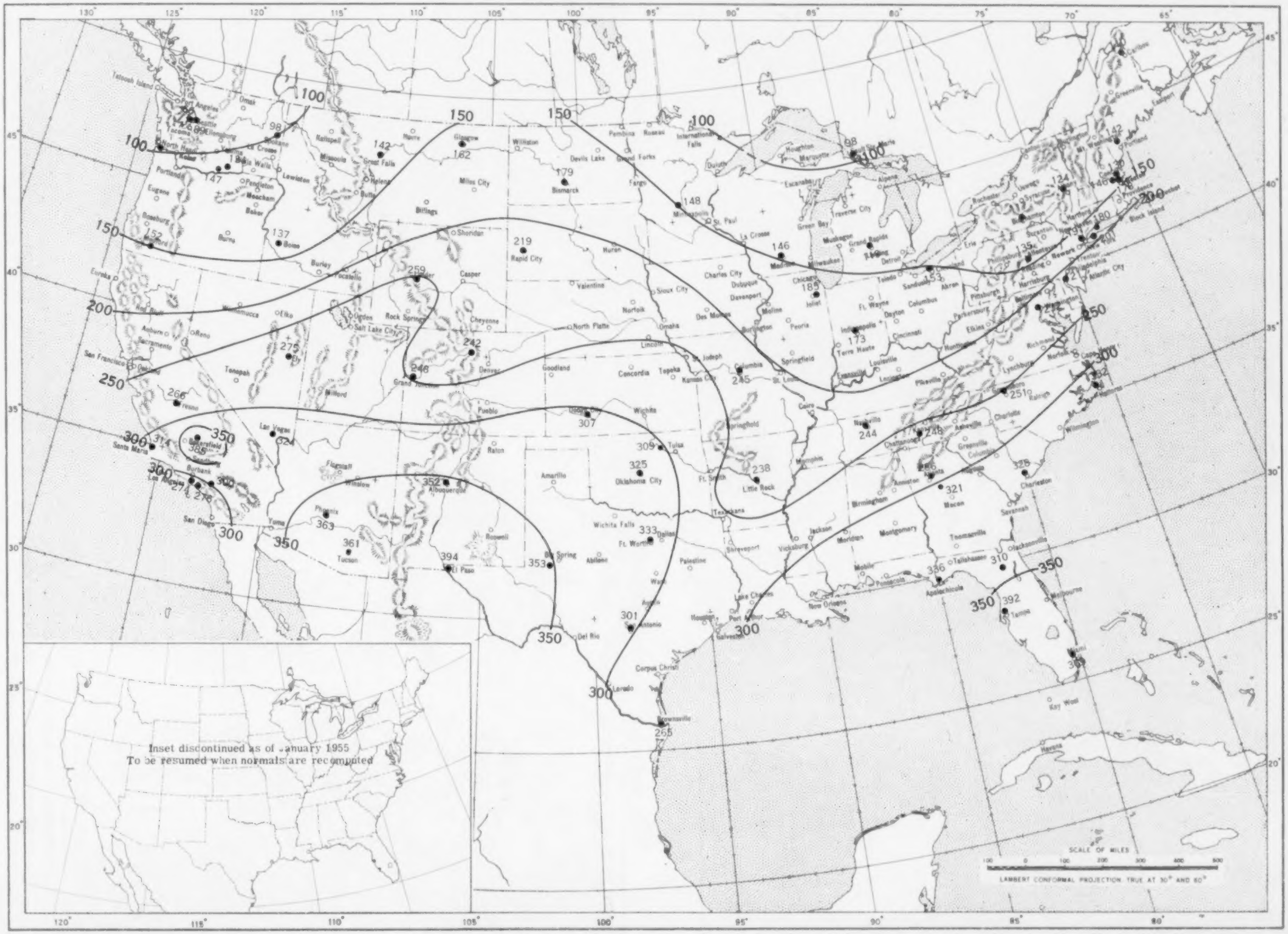
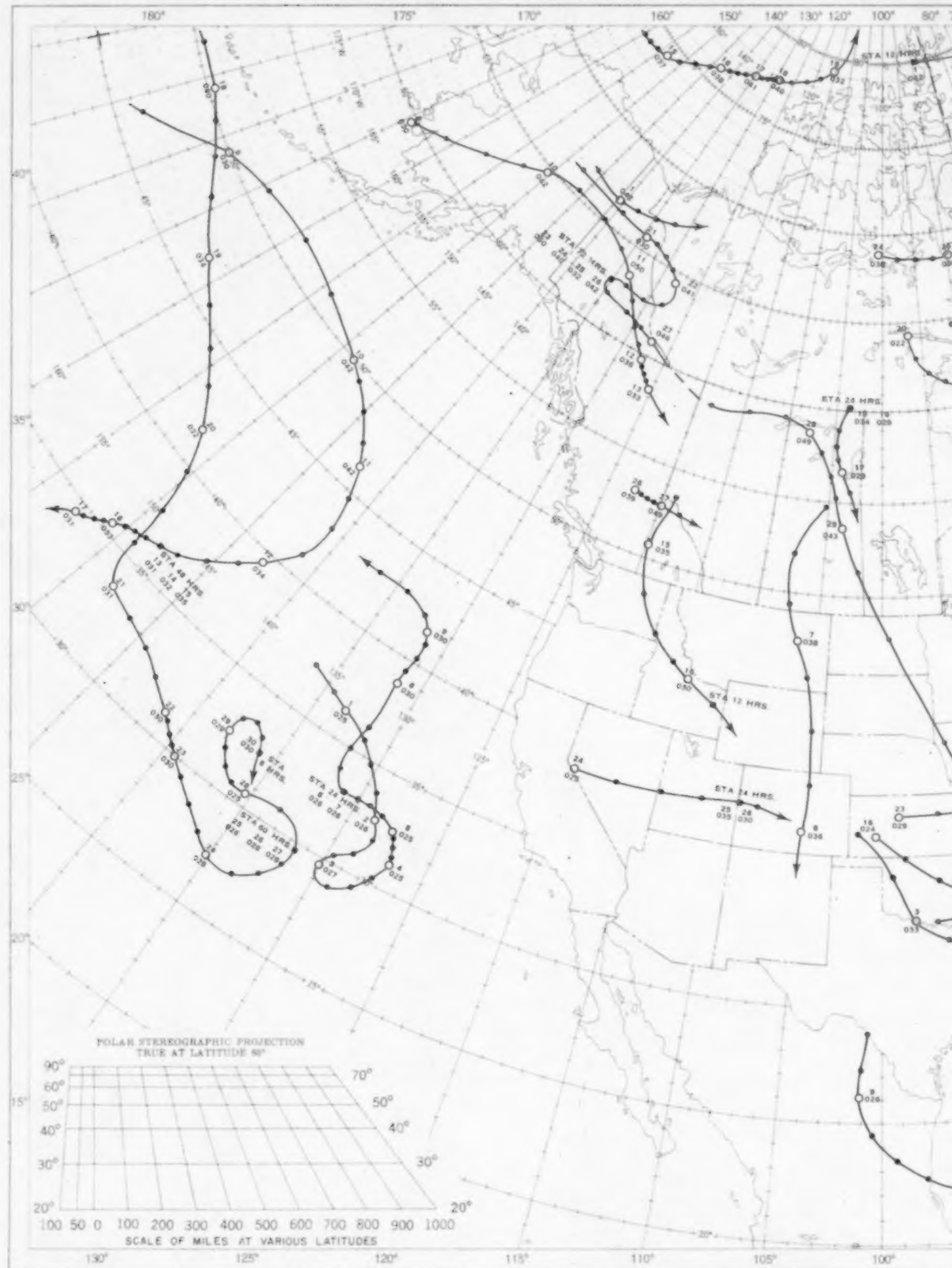


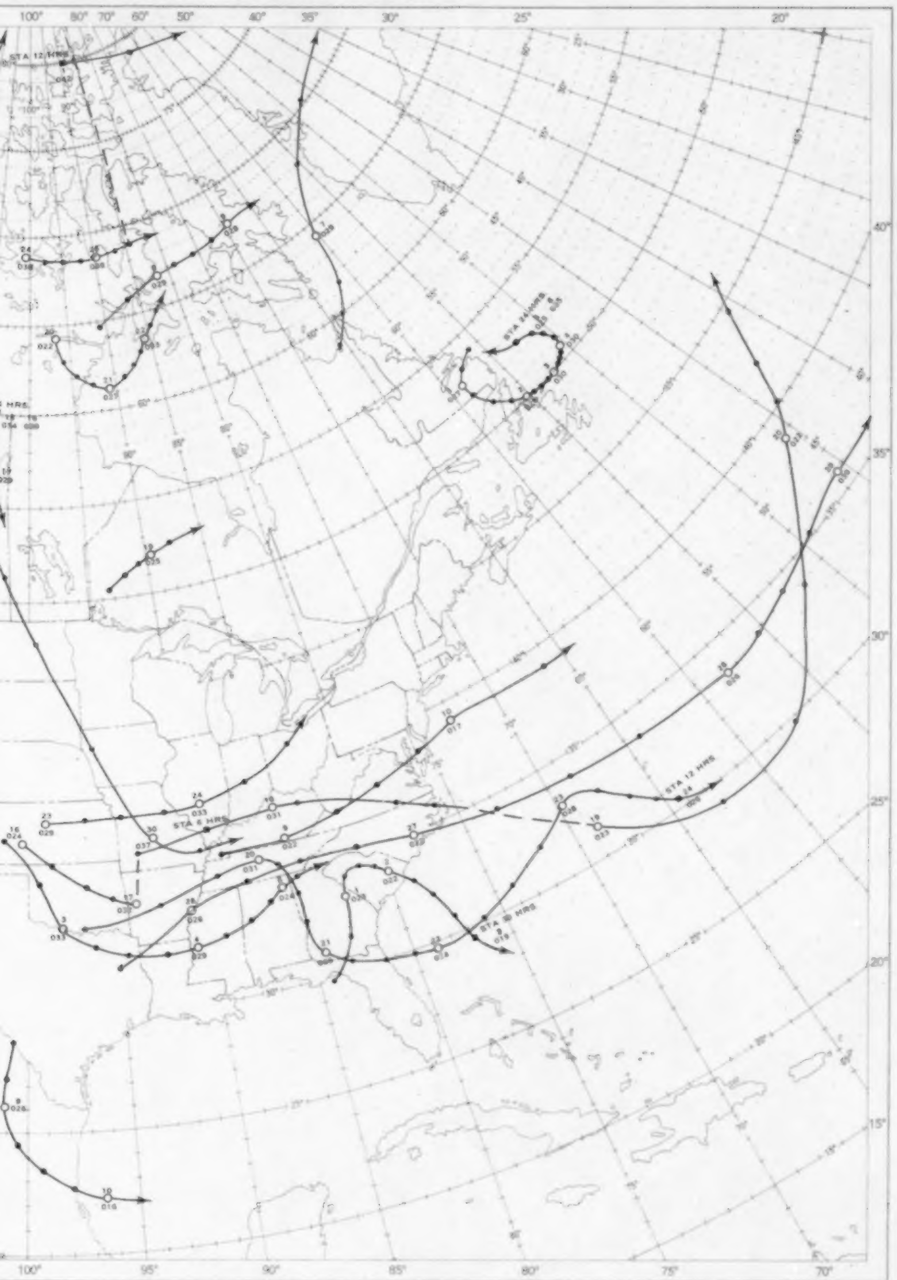
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Se



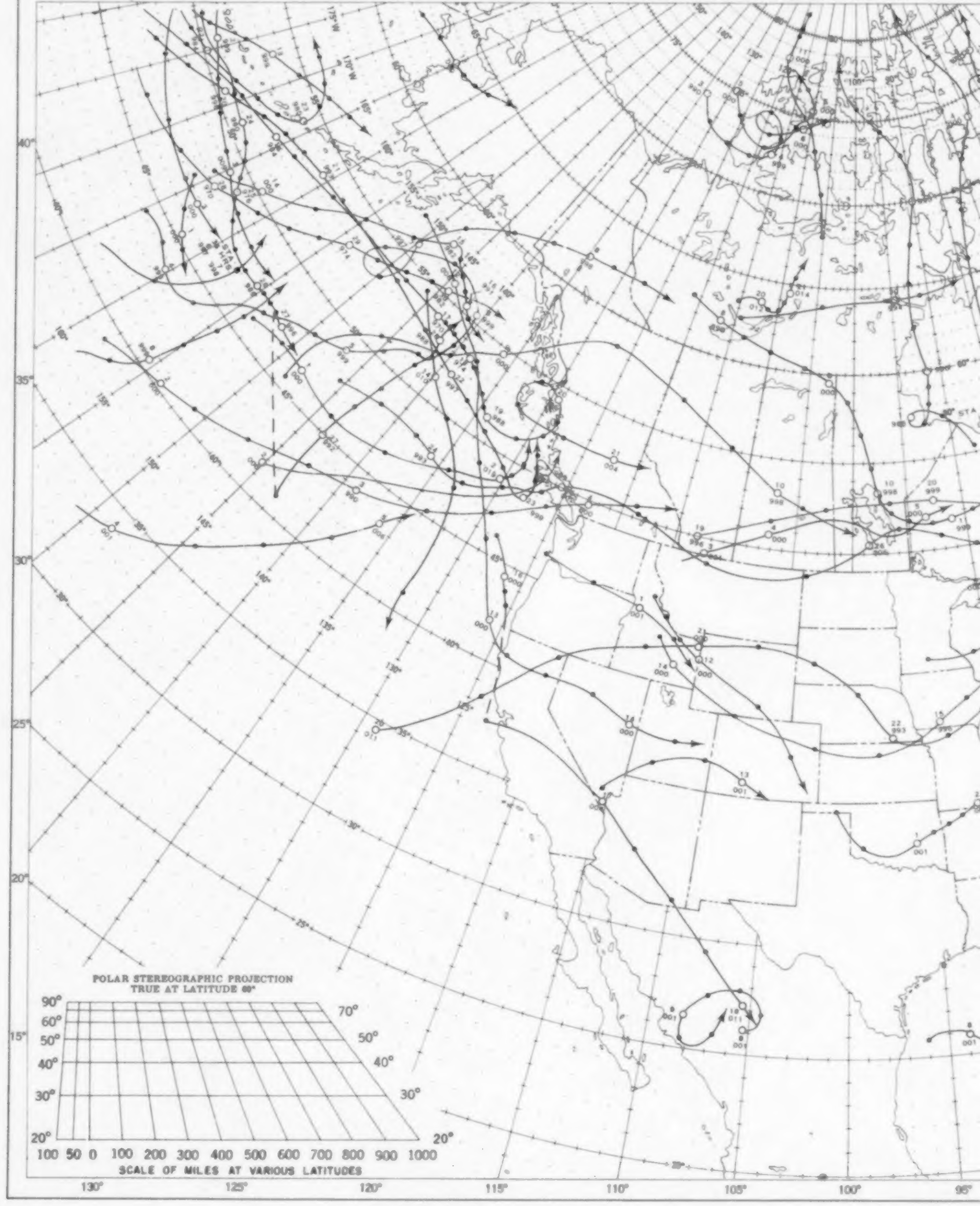
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circl
Dots indicate intervening 6-hourly positions. Squares indicate position of
indicates reformation at new position. Only those centers which co

es at Sea Level, November 1955. (Corrected)



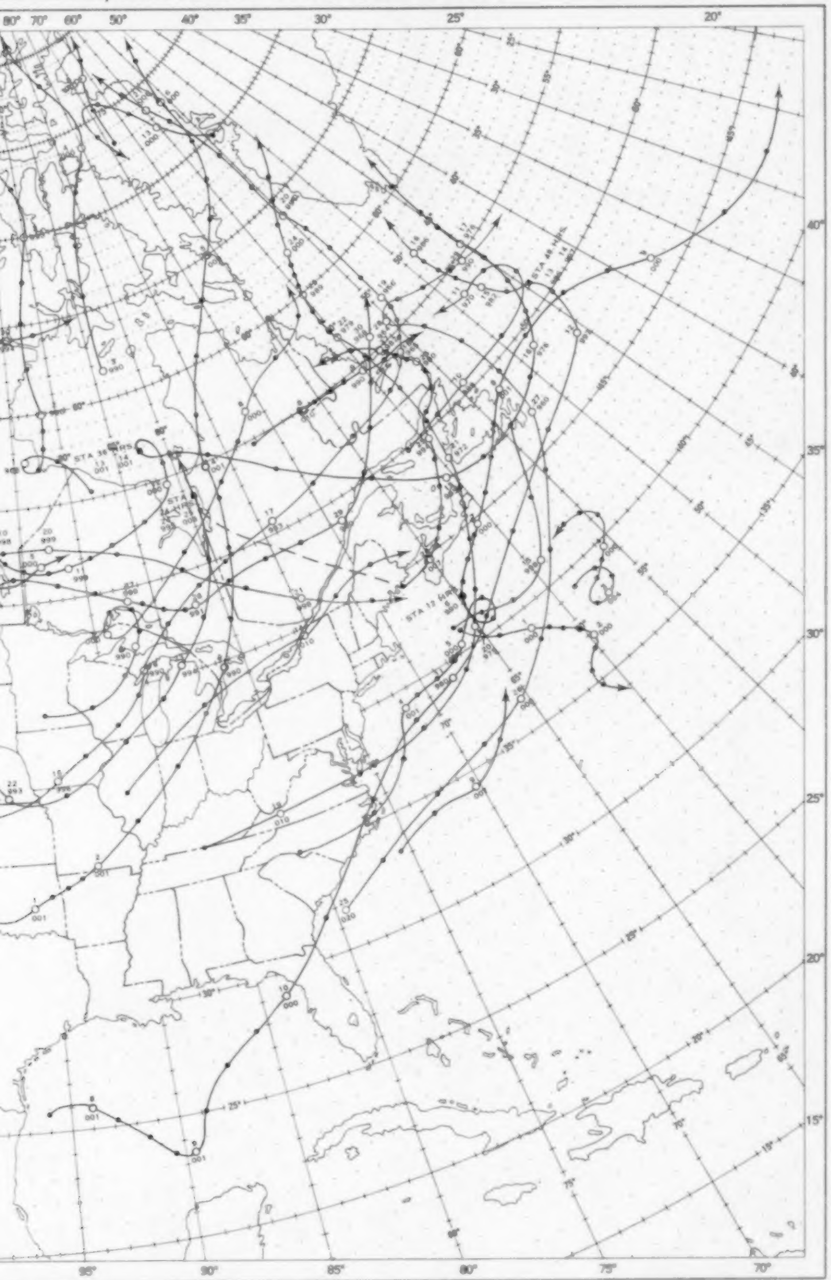
bove circle indicates date, figure below, pressure to nearest millibar.
osition of stationary center for period shown. Dashed line in track
s which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Leve



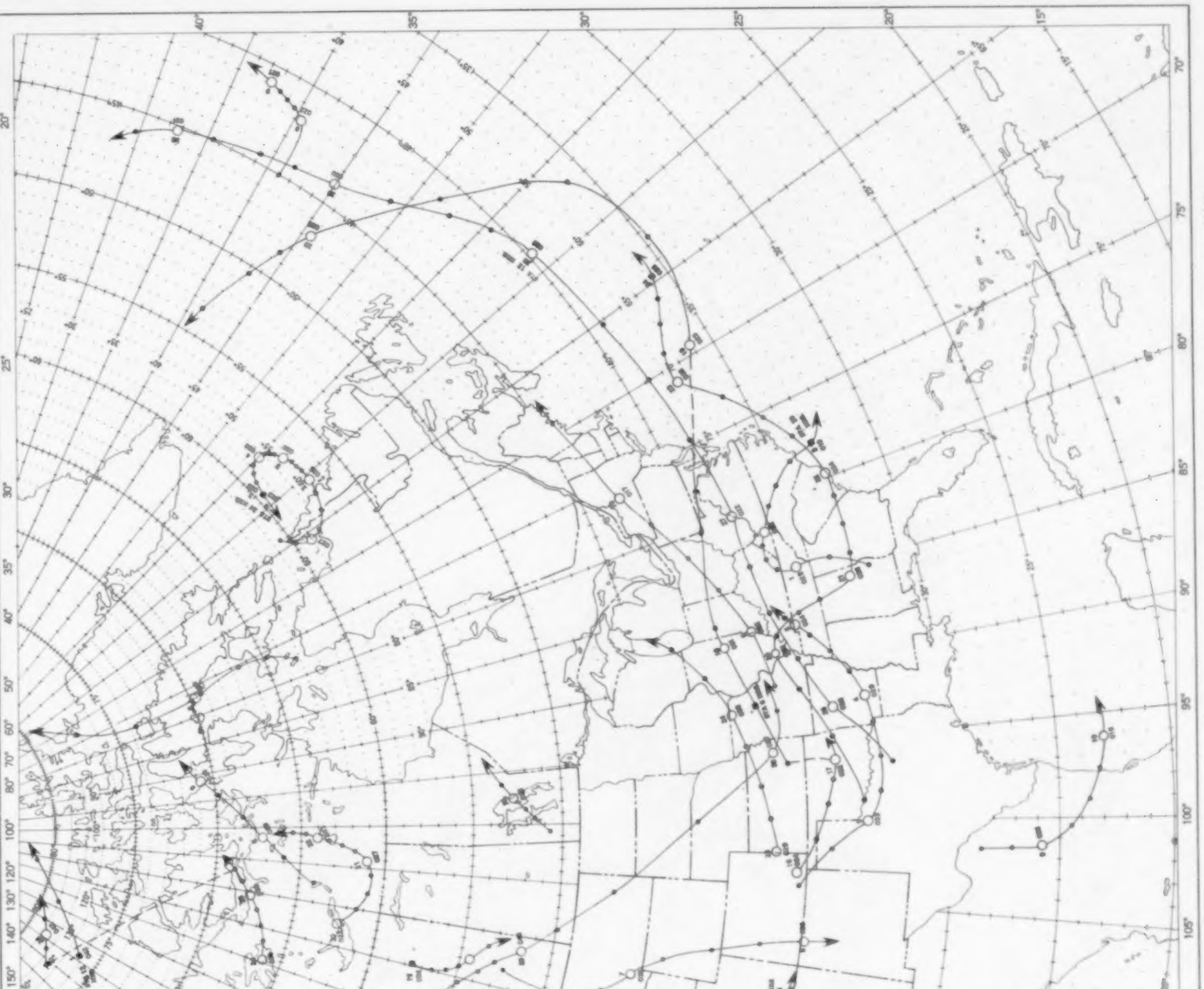
Circle indicates position of center at 7:30 a. m. E. S. T. See Ch

ea Level, November 1955. (Corrected)



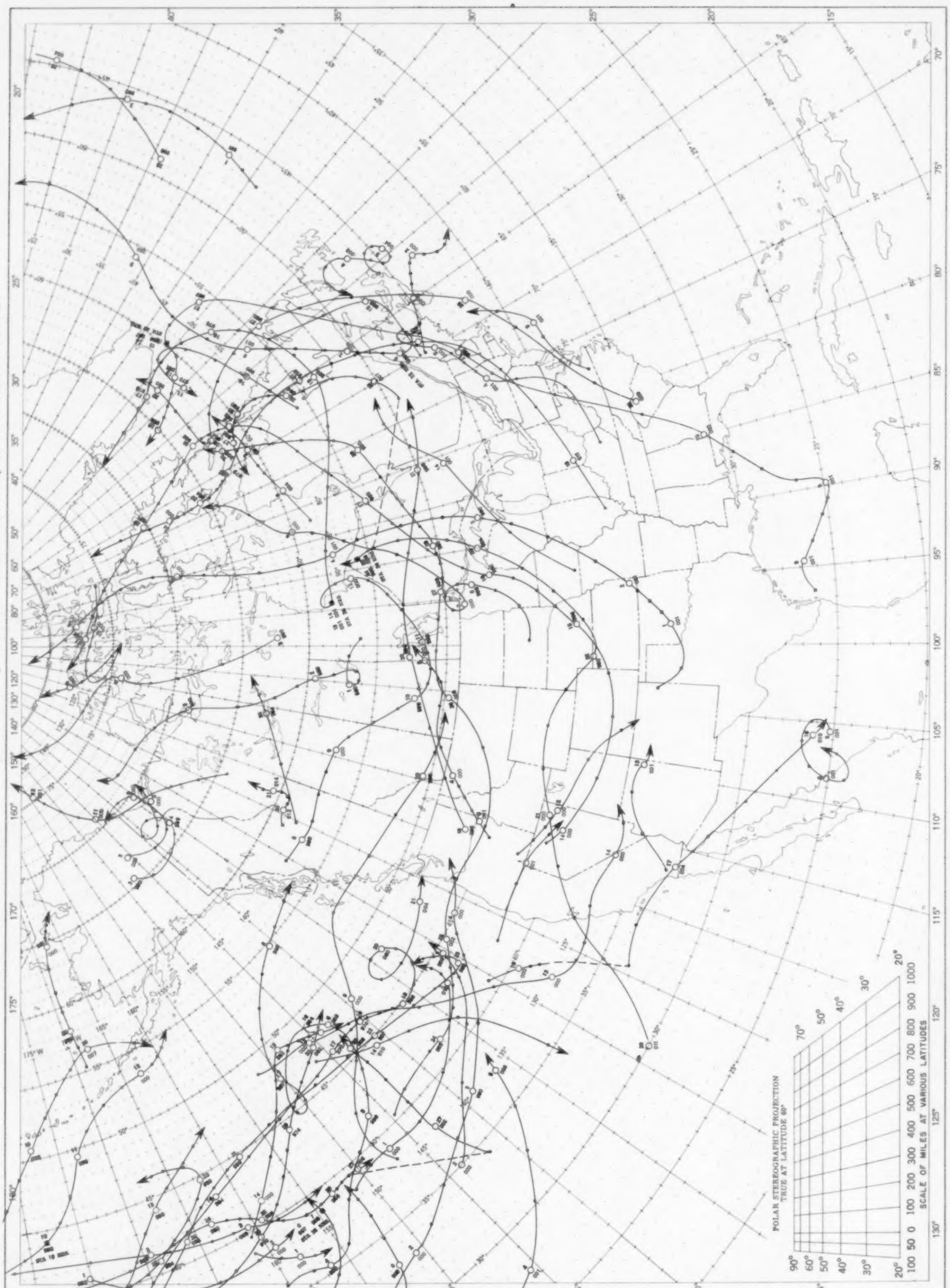
T. See Chart IX for explanation of symbols.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, November 1955.



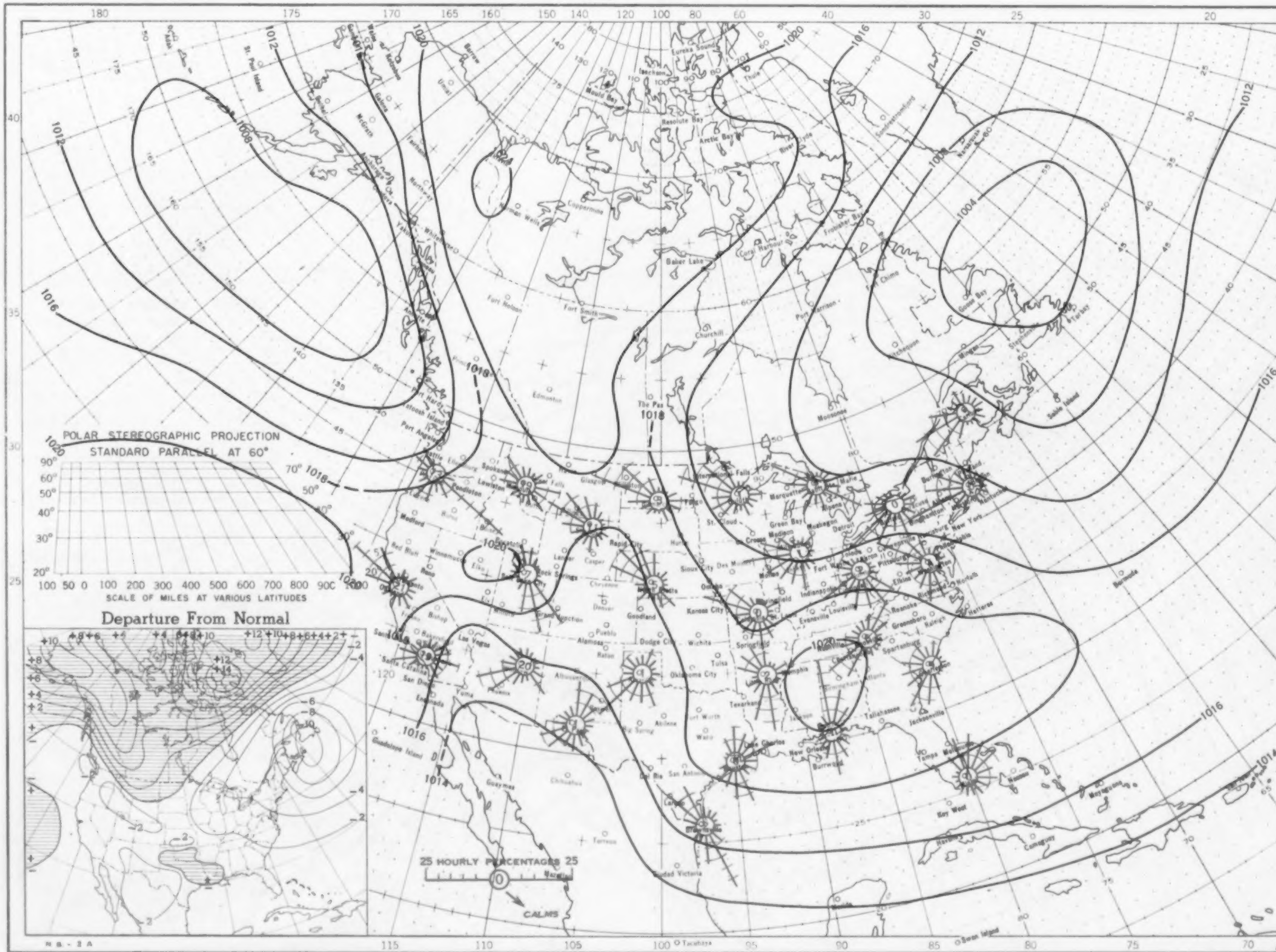
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, November 1955.



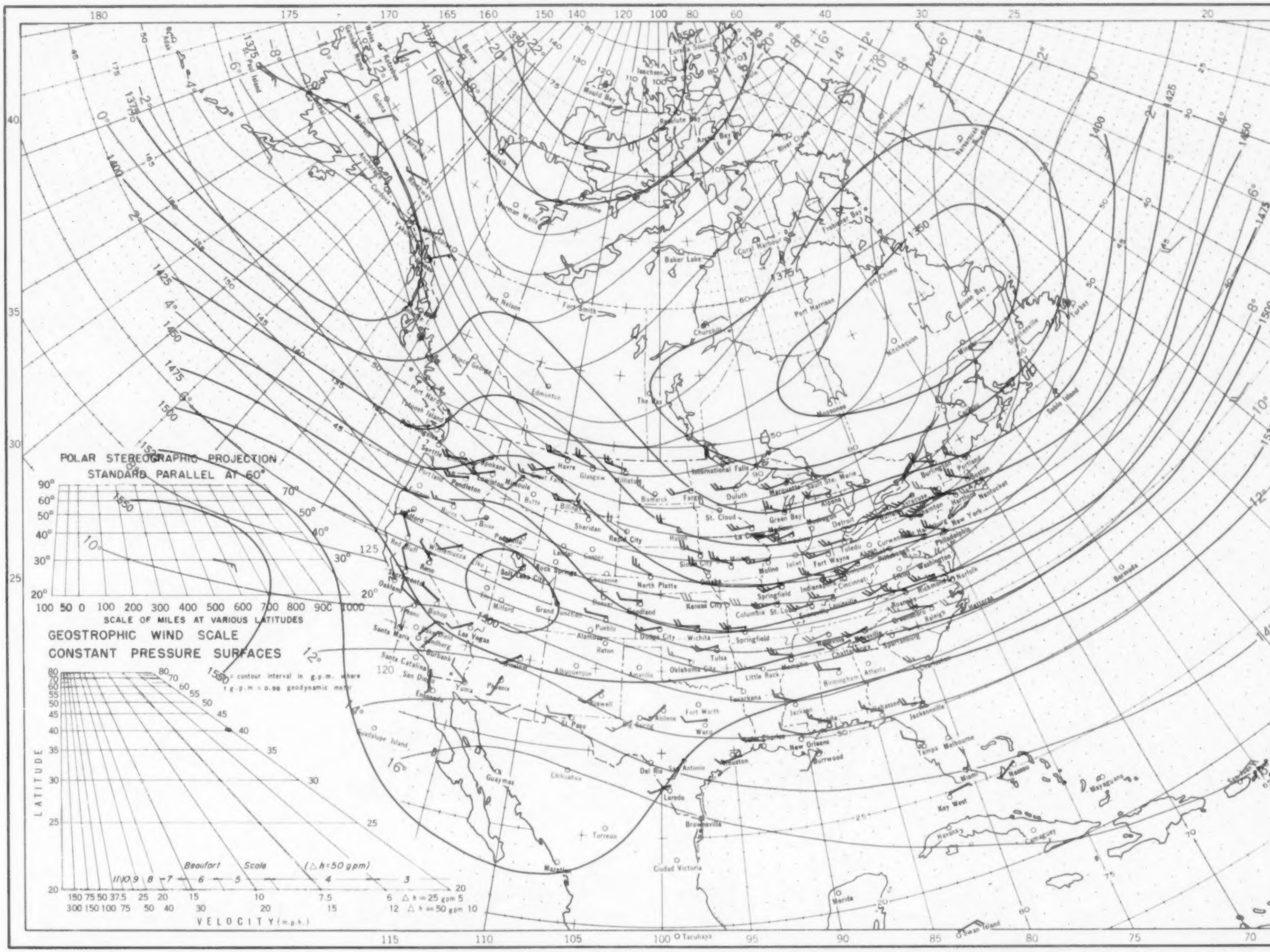
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, November 1955. Inset: Departure of Average Pressure (mb.) from Normal, November 1955.



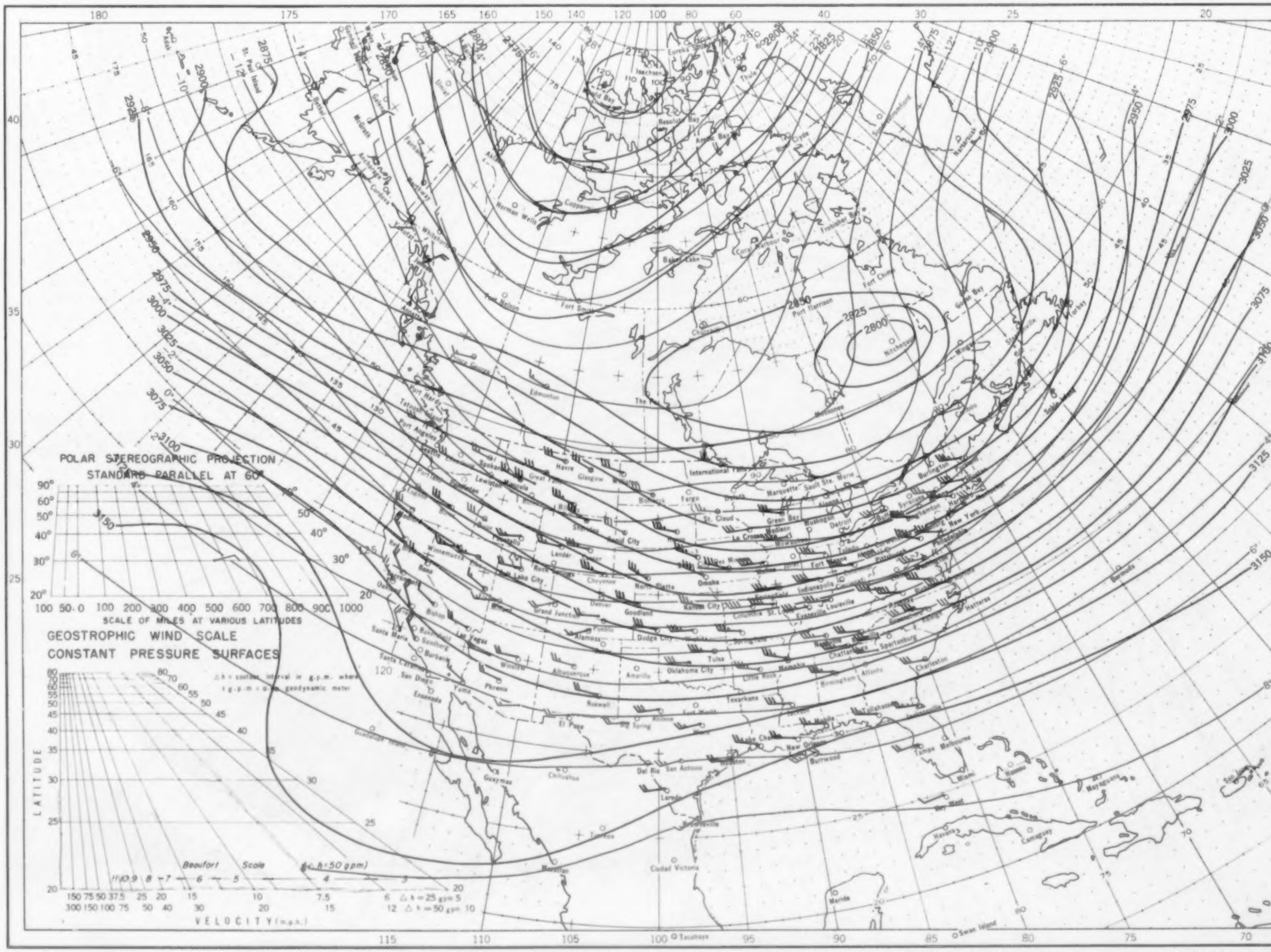
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), November 1955.



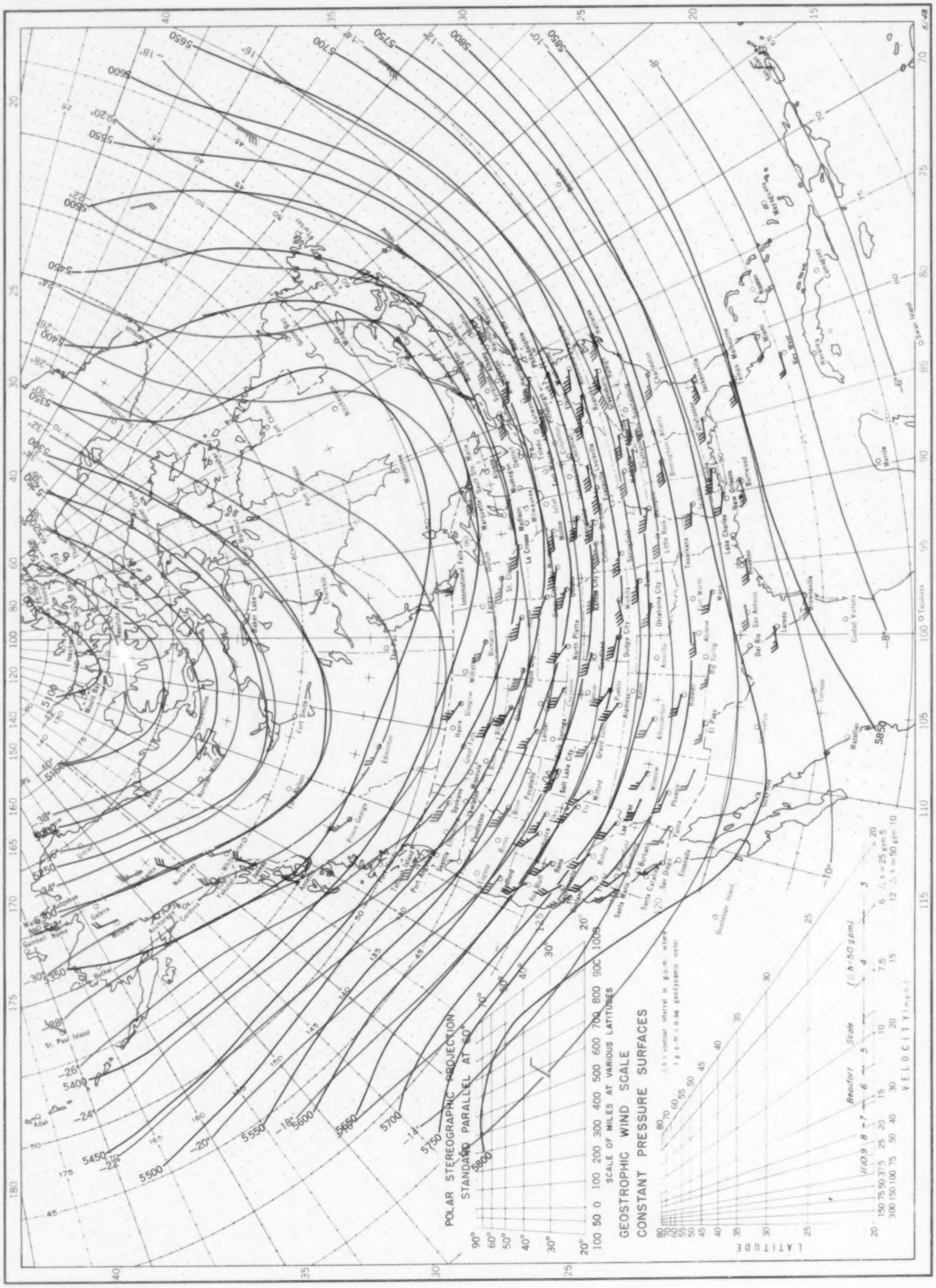
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), November 1955.



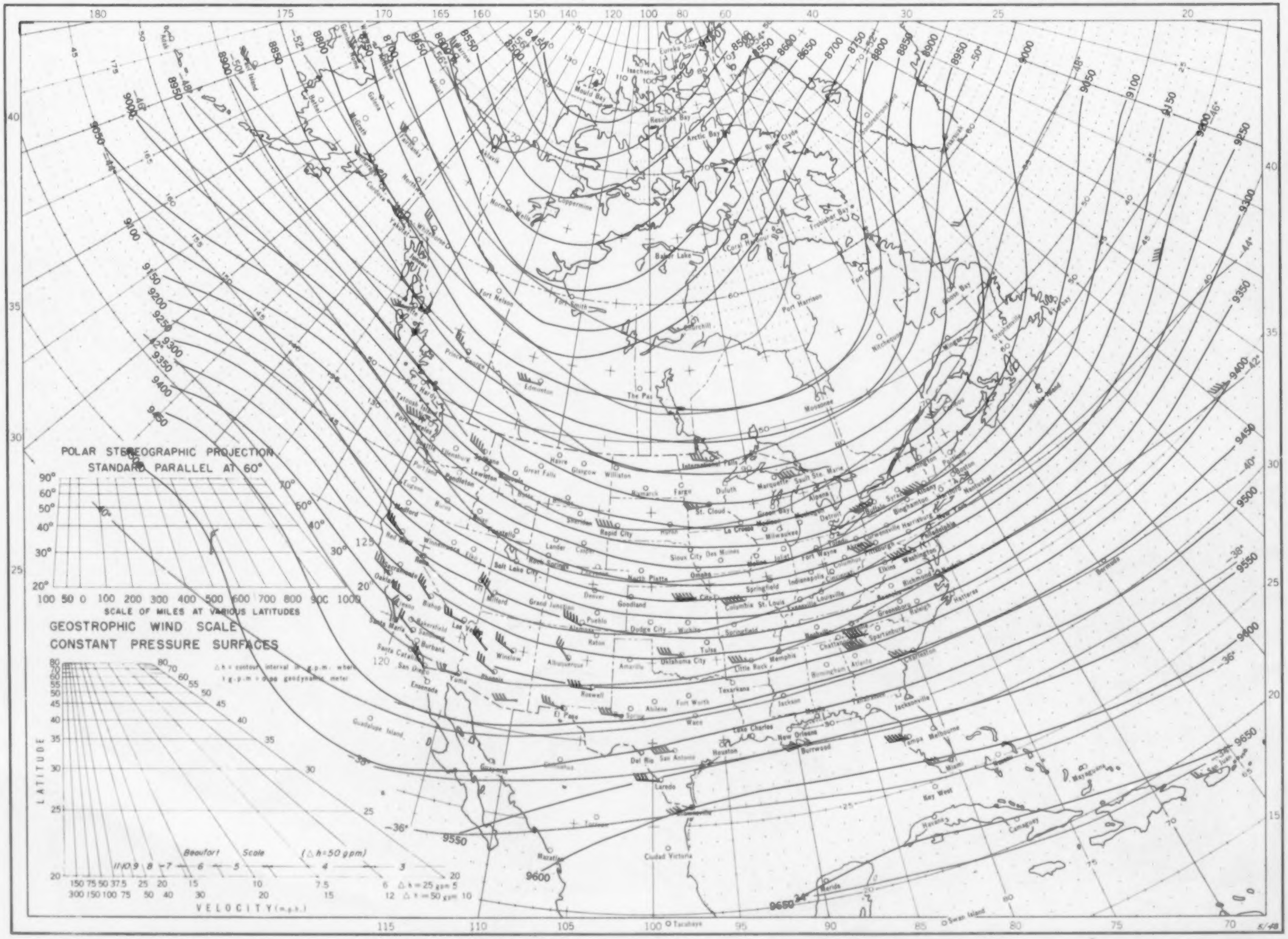
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), November 1955.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), November 1955.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.